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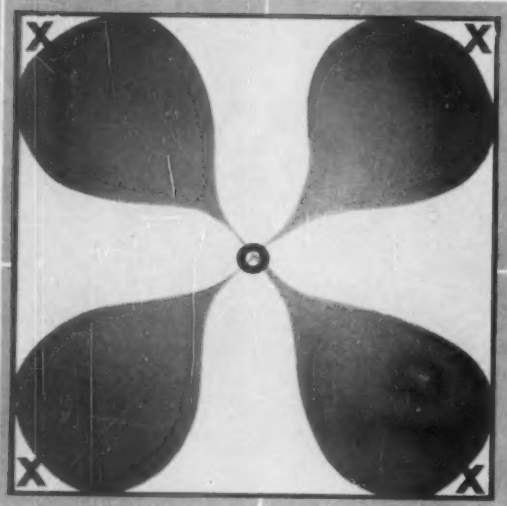

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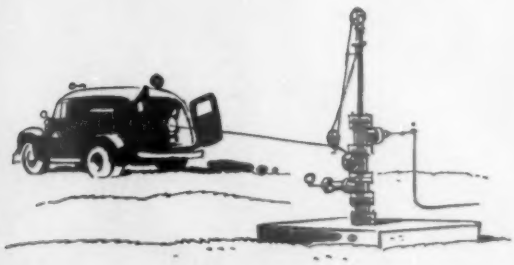

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On the Cover: An enlarged study of the area invaded by water at some intermediate stage of a water flood is superimposed on the background of a field with ideal five-spot flood patterns.

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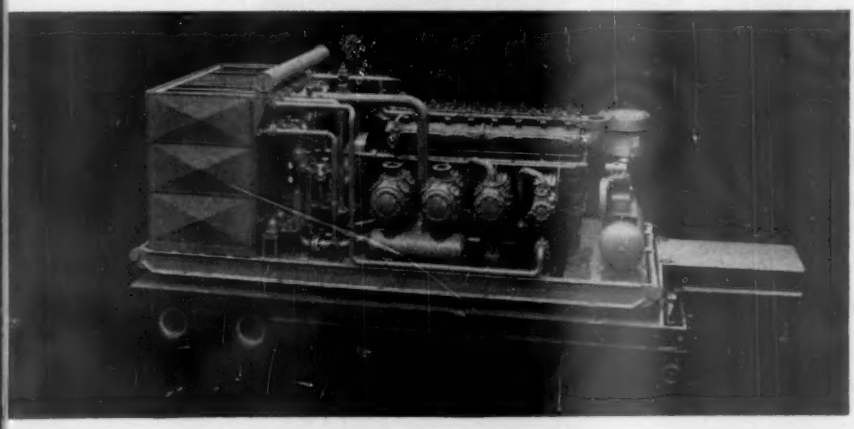

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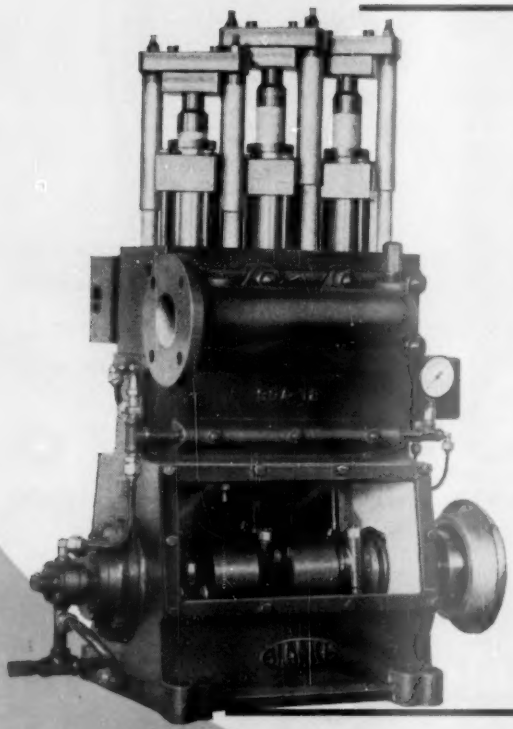

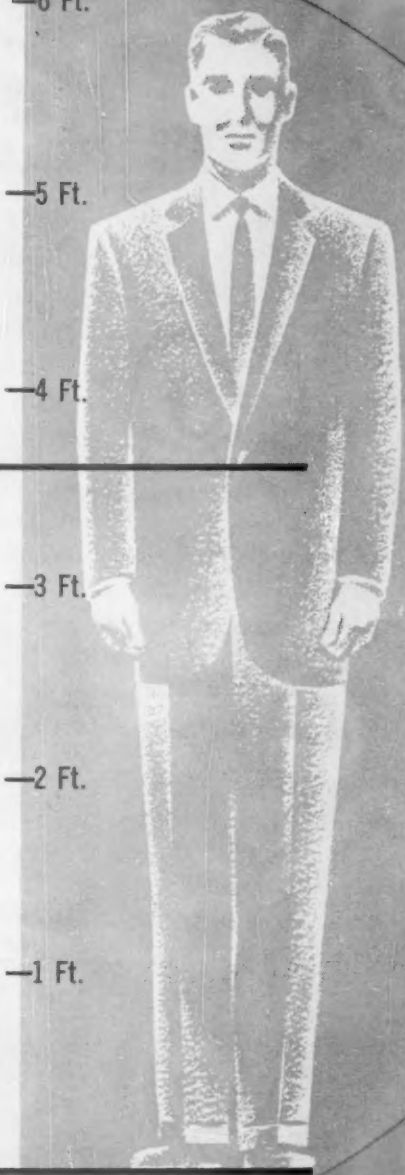

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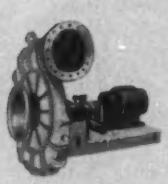

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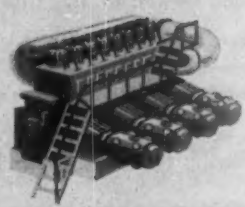

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EDITORIAL

SUCCESSFUL SYMPOSIUM REQUIRES MONTHS of PLANNING

E. MORRIS SEYDELL
MEMBER AIME

SEYDELL OPERATING CO.
WICHITA FALLS, TEX.

E. Morris Seydell was the general chairman of the Symposium Committee of the North Texas Secondary Recovery Symposium, which was held in Wichita Falls on Nov. 17-18, 1954. This meeting, considered as one of the best ever presented by an AIME local section, attracted 940 registrants from 19 states and Venezuela. The following article explains the work and planning done by the Symposium Committee, which had never before conducted such a meeting, and offers information designed to help other local sections which plan a similar meeting.

Information on Water Flooding

The Secondary Recovery Symposium held in Wichita Falls in November was the outgrowth of area demand for more information on water flooding. This material had to be presented on such a level that both the secondary recovery engineer and field superintendent would benefit. Since the North Texas district is largely an area of independents, the program had to be such that they, as well as company engineers, would find it profitable. This programming was accomplished by having a committee composed of members representing major companies, independents, consultants, and the U. S. Bureau of Mines. The program was for eight months in the various stages of outlining, paper acquisition, arranging, and presentation.

The committee is of the opinion that there are several fundamental factors that go into the successful presentation of a technical program. First and foremost is a strong, well developed program. In our case the committee even went to the degree of furnishing authors general outlines of papers to be written, so the program would have over-all continuity.

If it is decided that the program would be of wide interest and it is the desire of the group to present the material to a large number, publicity will play a major role. Direct mailing lists are available through the Petroleum Branch of AIME, the area trade associations, and, in the case of water flooding, through the number of associations solely devoted to secondary recovery. We found the trade journals and newspapers most cooperative in publishing our program.

The availability of hotel accommodations in some cases will govern whether the meeting should be more than one day. Local hotel and motel associations and the Chamber of Commerce can usually furnish the necessary information. It was also found that there are normally more accommodations available at certain times of the week than at other times.

Adequate facilities and proper equipment cannot be stressed too strongly. In most cases there is little or no way to determine accurately the number planning to attend; therefore, serious consideration should be given to having excess room rather than just enough. In most cases the cost will be about the same, The Petroleum Branch is in a position to furnish check lists of the necessary equipment and points of availability.

It was the unanimous opinion of our committee at the beginning of the undertaking that preparing preprints of all papers was most important. The present feeling, after the meeting is over, is even stronger for making preprints available. Preprints serve two functions: first, they give the registrant something in hand for his registration fee so that an adequate fee is justified; and, second, they serve as invaluable reference material during and after the meeting. The Petroleum Branch can handle the preparation of the preprints. We would not advise any group to attempt the handling of their own preprints unless they have had previous experience.

Pre-registration and Finances

Pre-registration and finances go hand in hand. The only expenses incurred up to the time of the meeting were the costs of program printing, direct mailing, and correspondence. If the size meeting that is desired has been decided upon, the initial costs can be accurately estimated and the necessary working capital ascertained. It was our experience that pre-registrations made it unnecessary to use any of the money set up as working capital. If preprints are to be furnished and the length of the papers to be presented has been designated, printing costs can be accurately estimated along with all other direct costs. From these costs a budget can be set up and a stable financial position maintained.

The most difficult item of finance to control is the banquet or luncheon. In almost all instances guarantees have to be made well in advance for such functions. Many registrants coming from some distance will choose to purchase their tickets upon arrival. Serious consideration should be given as to the real value of such functions if a balanced budget is an important factor.

Where large meetings are planned, strong adequately-staffed committees will serve to take the load off of the main committee which has already spent many months in planning and preparation.

Although the presentation of this meeting proved to be a difficult and time-consuming job, the North Texas Local Section is extremely proud to have undertaken it. Among the many advantages gained by the local section were increased prestige, a valuable list of prospective members, and a strength acquired through all of the members working together toward a common goal. ★★★

FEATURE ARTICLE

ECONOMICS of WATER FLOODING

L. L. BRUNDRED
LATHAM L. BRUNDRED, JR.

BRUNDRED ENTERPRISES
ABILENE, TEX.

Abstract

Water flooding has progressed from the haphazard experimental stage through numerous phases to a somewhat precise engineering achievement. Unfortunately the economics, which are dependent on so many variables, have not yet lent themselves to particularly accurate interpretations.

Recognizing that technical studies are proceeding rapidly, there still are divergent schools of thought. Regardless of divergencies of opinion, the first step in any proposed project is a complete engineering study, evaluated in the light of past experience.

The economics fundamentally boil down to the component parts of the following simple formula: Expected Gross Revenue less The Summation of Computed Acquisition Costs, Costs of Development, and Operating Costs (over the life of the flood) equals Estimated Gross Profit.

Estimated Gross Revenue can be fairly reliably determined from the initial engineering study. Acquisition costs must be based upon the true value of the property and are always subject to negotiation. Development costs are influenced by many factors, but are largely controlled by the depth and the spacing used. They can be estimated with reasonable accuracy once the spacing program has been adopted. Operating costs do not lend themselves to ready determination because of the variables involved, but reasonably accurate estimates are possible.

There is no substitute for experience. Approximately seven out of 10 waterflood attempts are failures. It is just as important to determine basic causes of failure as it is to study successful floods. Good floods are widely publicized, the poor ones never. Most of these failures can be attributed to improper engineering, lack of experience, or shortage of working capital.

Engineering and economics are inseparable, and a proposed flood, based on sound engineering, must meet heavy financial demands. While water flooding is often considered one of the safest of oil ventures, it, too, can be hazardous. "First results" are often long delayed, and pay out is invariably slow.

The conclusion is inescapable that successful water flooding requires three basic essentials: engineering, experience, and economics.

Paper given at Secondary Recovery Symposium presented by the North Texas Local Section of AIME and sponsored by the North Texas Oil and Gas Association, Nov. 17-18, 1954.

Introduction

The oil producing business is logically divided into two main classifications with certain calculated risks and varied rates of return.

Primary Production

In the early life of a producing field, primary production is invariably the most lucrative end of the oil business. Costs can be accurately predicted. Decline curves, revised from time to time, can be relied upon for estimating future production and revenue, provided the price of crude oil remains fixed. However, as wells approach the stripper well class, ever-diminishing returns make this type of production less and less attractive, and the point (economic limit) is finally reached where something must be done. At this spot on the decline curve, there are only three courses left: (1) abandonment to prevent losses; (2) sale to some operator with lower overhead who can still make a small profit; or (3) secondary recovery.

Secondary Recovery

This paper deals only with this phase of the oil business and is confined to the waterflooding method of secondary recovery. Before starting the discussion, it is well to sound a word of caution. Water flooding, too, has its attendant risks, but above all, the rate of return is slow, *very* slow. Detailed engineering studies are essential; capital investments are high; and the time lag before any results are secured, followed by the long period required for pay out, is discouraging to many operators. Only experience in water flooding can prevent many mistakes that spell success or failure.

In short, there are three basic essentials, all beginning with an *E:* engineering, experience, and economics.

Any analysis of the economics of water flooding brings into account so many variables that it is almost impossible to fix any hard and fast rules which say, "If these are true, this flood will be a financial success." No two floods are alike and there is no such thing as an economic yardstick. While there are many factors which must be balanced against each other during the investigation period in an effort to determine the feasibility of a water flood, we have, through experience, evolved certain procedures which permit the pieces of the puzzle to fall in place in their proper order. By the same token, assuming that the preliminary investigation is satisfactory and that a flood has been started, many other factors are constantly arising which must

be balanced against each other. Thus, water flooding requires a constant study of engineering and economics, and the task is not completed until the property is ready to be abandoned.

Engineering Study

Engineers, scientists, and research laboratories are constantly at work on secondary recovery problems. The economist must evaluate any new proposals on a dollar-in, dollar-out basis. Theory must be able to withstand the cold glare of an economic spotlight.

Since the engineering and economics are so closely dependent upon each other, this paper perforce must deal with both. It goes without saying that the initial approach is an engineering study to determine if a given property fulfills certain criteria which are essential for any waterflood project and that the cost of such an investigation is part and parcel of the over-all cost of any proposed flood. The starting point, therefore, is the following questions, which have to be answered before any computation of economics can be satisfactorily concluded.

1. Area. Is the pool located in a suitable area insofar as other operations of the company are concerned? Can it be supervised efficiently from present headquarters? Are trained personnel available for that area?

2. Cost of Acquisition. Is the present production in the stripper class with resultant lower acquisition cost, or is the area producing flush primary production with consequent higher acquisition cost?

3. Acreage. Is there sufficient acreage available to permit eventual spread of the fixed costs of a water flood, such as overhead, water plants, supply wells, and general property items in order to provide a low cost per acre?

4. Ownership. Does the preliminary survey of the area indicate present owners with whom it would be possible to deal on a reasonable basis?

5. Depth. Is the formation to be flooded so deep that it might entail prohibitive development costs, or is it too shallow to resist reasonable sand face pressures?

6. Abandonments. Have the number of wells abandoned to date (generally improperly plugged) been excessive?

7. Type of Reservoir. What type of primary drive was responsible for past production: (a) water drive (b) gas-cap drive, or (c) gas-solution drive?

8. Sand Thickness. Is there sufficient sand thickness in relationship to the depth to permit reasonable recoveries per acre or per acre-foot?

9. Porosity. As a measure of capacity, is there sufficient pore space for the reservoir still to hold reasonable quantities of residual oil?

10. Oil Saturations. Is there sufficient oil in place to justify a water flood?

11. Water Saturations. Has edgewater or infiltration from other zones destroyed the floodability of the reservoir? Does evidence point to a watered out sand?

12. Permeabilities. Is the range of permeability sufficiently uniform to prevent channeling of the injected water through highly permeable streaks; also, is the average permeability high enough in relationship to the depth to preclude the necessity of high plant pressures?

13. Viscosity of Oil. Is the centipoise rating, largely parallel with gravity, low enough to prevent surface tension from interfering with free movement of the oil? Is the mobility ratio good enough to provide adequate sweep efficiency?

14. Initial Production. Was the initial production of the average well high enough to indicate a locally well-saturated, well-pressured reservoir?

15. Primary Recovery. Was the primary recovery per acre from this pool large enough (with or without gas or air repressuring), and was it recovered over a long enough sustained period to justify the belief that water flooding may produce a "second crop" approximately equal to the primary production?

16. Availability of Injection Water. Is there sufficient water, fresh or salt, available within a reasonable distance of the proposed project to provide satisfactory rates of injection for the entire pool, bearing in mind that some formations cannot be successfully flooded with fresh water and that some salt waters cannot be used because they form insoluble salts?

While many other items, such as terrain, condition of roads, physical condition of equipment, availability of labor and contractors are all taken into consideration, they have but little influence on the final determination of costs vs revenue.

Admittedly, these are primarily engineering questions, but unless such engineering data is carefully considered, there will be no foundation on which to base an economic study of the project.

Evaluation of Engineering Study

After the data on all of the above points have been collected, the answers to several of these questions then must be further evaluated in the light of certain basic principles, which are considered of tremendous influence in determining both the engineering and economic floodability of a given area.

Depth

The depth controls at least part of the sand face pressure. If too much added pressure is required, pressure parting, lifting of the overburden, or breakthroughs can readily occur. While these troubles are almost always a function of permeability and, to some extent, of the spacing used, reasonable depths are very desirable. In general, initial formation pressures increase in proportion to the depth; hence, the deeper the horizon to be flooded, the more sand face pressure it will withstand before encountering difficulties affecting ultimate recovery.

Abandonments

While far from universally practiced, the authors consider it essential to reopen and replug any and all wells drilled within the area to be flooded, even so-called dry holes, in order to prevent escape of oil and/or injected water into zones not being flooded. A dry hole might have only a few inches of formation uncovered and yet be the source of tremendous loss of valuable oil. Such losses reduce expected recovery and add materially to costs.

Type of Reservoir

1. Few waterdrive fields lend themselves to successful flooding, particularly if the force of the drive has penetrated up-structure sufficiently to flood out the zones under consideration Water-wet sands are hazardous. Efforts to flood either of them generally result in production of very large quantities of water and little oil. A ratio of injected water to oil produced in such cases of 20, or even 40-1, is not at all uncommon. Such floods are seldom profitable.

2. Gas-cap drive fields offer a different type of hazard

based primarily on the fact that the permeability of the gas part of the zone is generally higher than the oil saturated zone. Water injected into the entire zone, under such conditions, almost invariably moves preferentially through the gas-cap, allowing little movement of the water through the zone of lower permeability. It is unfortunate, but quite true, that while residual oil in place underneath a gas-cap type of field is usually very high, to date no means have been found to control the injected water so that it will affect only that zone containing free oil. Again such floods are seldom a financial success.

3. The gas-solution drive field, either in sand or lime, is recognized as offering the greatest opportunity for success.

Sand Thickness

To date, water flooding has been confined almost exclusively to the older fields. Drillers' logs are generally the only source of subsurface information prior to the taking of cores, and little reliance can be placed on such records of sand thickness. A discount factor of perhaps 25 per cent is justified. Even with a few cores available, some sort of discount factor is still indicated at least until development work has progressed to the point where complete factual information is available. Some argue that certain floods will not stand the cost of coring each input and producer, but as input rates and pressures are entirely dependent upon sand conditions encountered in any given well, the authors lean strongly to coring at least every input well, and consider the cost justifiable, in light of the information gained.

Porosity

Variations in porosity within a given field are widespread; shale or lime intrusions are often found and even dry holes with little or no porosity can be encountered in the heart of a pool. The use of the word "average" in connection with "porosity" thus takes on added significance, as there is no way to compensate for harmfully low porosity.

Oil and Water Saturations

Among engineers, the reliability of laboratory saturation determinations is probably one of the most controversial subjects involved in water flooding. The methods used in determining saturations in the laboratories have not yet reached the scientific level where all engineers are agreed upon a uniform yardstick. The penetration of the zone by the core bit, always under pressure, can so radically alter the current subsurface conditions that little reliance, at least in the authors' opinion, can be placed upon these laboratory findings. This injects a certain element of risk in any calculations, and the answer must be sought elsewhere.

Permeabilities

Low permeability is not necessarily a deterrent to a successful flood — provided of course, that the zone is at sufficient depth and the spacing, water to oil, is not abnormally long. However, zones of low permeability mixed in with streaks of extremely high permeability in a number of input wells provide one of the greatest hazards to water flooding. Uniformity within any given well is extremely desirable, but it is recognized that this uniformity does not necessarily have to cover an entire pool. In fact, many successful floods are being conducted where permeability is uniformly high in one part of the field and uniformly low in the balance of the field. Lack of this uniformity can cause channeling and result in serious failure.

Initial Production and Primary Recovery

Being unable to place too much dependence upon laboratory oil and water saturation determinations, one must study initial and primary figures, if available, in the hopes of obtaining clues to subsurface conditions. This study can be made prior to acquisition of the property for waterflooding purposes. It is not a too well recognized fact that, aside from the hazard of gravity drainage, many fields which have produced excessively large amounts of oil per acre lend themselves admirably to water flooding. This seems to contradict itself, as it is natural to assume that the greater the quantity of oil removed from the reservoir, the less would be the amount to be recovered under flooding. In such fields, however, quite high initial oil saturations were doubtless present, perhaps 35 per cent to 55 per cent. Surface tension of the oil in the reservoir probably was low and the reservoir drive was highly efficient. Thereafter, the unrecoverable residual oil after flooding is always low. Instead of 19 per cent to perhaps 25 per cent, it often is as low as 13 per cent to 17 per cent. It is mainly this sharp reduction in unrecoverable reserves that accounts for many of the outstanding successes in waterflooding this type of reservoir.

Economic Studies

It is obvious that the economics of any water flood project boil down to the simple formula:

Gross Revenue less All Costs equals Gross Profit.

Using the information collected in the engineering study, the factors making up this formula can now be determined.

Gross Revenue

A reliable estimate of the gross production can be obtained from the engineering data determined above. This, multiplied by the expected price per barrel over the life of the flood, provides the gross revenue to be expected. The progress of the production should be checked and rechecked constantly against "typical" decline curves, and the ultimate recovery analyzed continuously in light of new laboratory and engineering findings, new cores, and previous experience.

Although water flooding almost invariably results in 1° to 3° rise in gravity, the authors prefer to disregard the usual increased revenue resulting therefrom, electing to use it as a factor of safety.

Costs

Before discussing in detail acquisition, development, and operating costs, it should be pointed out that water flooding is not cheap. If done properly, and this is the only way in which maximum recovery can be secured, tremendous capital is required for development and operation, to say nothing of acquisition costs. Development costs alone can run between $1,500 and $5,000 per acre. Operating costs over the life of the flood will generally lie within these same limits, particularly when the cost of reopening and replugging of old wells, so necessary in a successful flood, is included.

Cost of Acquisition

Without question, the cost of acquisition is of paramount importance. There is no fixed method which can be used to determine what should be paid for a property, but the authors have found it most desirable to calculate the value of the property to be purchased predicated on the assumption that all cash will be required. The cash figure thereafter can be used as a base formula for all future computations. This opens the field to unlimited variations for the purpose of negotiation, such as oil payments, overriding royalties, and guarantees of income, or unlimited combinations of such factors. However, extreme care must be taken to discount each proposal to present worth or back to the true value of the property. It goes without saying that overriding royalties, being a permanent burden on the property, are the least desirable from the viewpoint of the purchaser. In most cases, the type of deal which can be made is dependent upon the financial position of both the purchaser and the seller, particularly upon the tax position of the seller. Where the seller has a low residual cost, he is seldom interested in cash. Of late, fixed oil payments, in lieu of overriding royalties, have come into great favor, where the Capital Gains Tax of 25 per cent is far less than straight corporate income tax or individual taxes. The wise seller seeks the advice of his tax attorney. The wise buyer does not pay too much or overburden his property with heavy overriding royalties or oil payments.

Development Cost

The main factors influencing any determination of development costs are: (1) spacing, water to water; (2) use or non-use of existing wells; (3) use or non-use of second-hand equipment, either located on the property or purchased; (4) type of water plant; and (5) pumping vs flowing.

Spacing controls the number of input and producing wells to be drilled and this, in turn, largely controls the development cost per acre. Spacing is probably the most variable of all factors influencing costs. Engineers seldom agree on what is known as an "ideal spacing." Pressure gradient curves would lead one to the belief that spacing can almost be limitless, but in actual practice, such is not the case. For example, in one very shallow field producing low gravity oil, a spacing of 150 ft water to water was found to be too long. On the other hand, a well density of 1.8 acres in one of the Shoestring sands of Eastern Kansas was found to be too close. Successful from a production viewpoint, a wider spacing would have given almost the same recovery but much lower development cost.

While in one field, 1½-acre spacing might be entirely satisfactory. In others, 5 acres, 10, or even 20 acres, might satisfy both the engineering and economic aspects of the project.

We do not mean to convey that considerable latitude in the selection of proper spacing is not permissible, but sweep efficiency must be balanced against development and operating costs. While engineering may dictate relatively close spacing, economics may lengthen this spacing materially. The real struggle is time vs cost. A satisfactory balance between the two must prevail.

Existing wells may or may not be used. Here again, this problem is the subject of endless discussion. While the authors believe in pattern drilling, we do not hesitate to use an old producing well as a producer provided it is located not more than 10 per cent off the desired geometrical location, and provided, of course, it is in proper physical condition.

In many cases, such wells are not in good physical shape and require either cleaning out, replacement of casing, or some other major expense. These costs must be taken into consideration as part of the development costs whenever such a well is intended to take the place of a new producer. As for using such a well as an input, the hazards involved in its conversion, the doubtful efficiency as an input after conversion, and the cost of the work seldom justify the expense involved—even if it is very close to a proposed pattern input. Any saving in converting such wells to inputs is considered negligible. The authors prefer to drill new input wells, coring each of them and consider such coring as an integral part of development costs. In this connection, considerable saving can be made through careful selection of contractors. They are always eager for this type of work as each move is measured in feet, rather than in miles, and the going price per foot is subject to considerable discount.

Use of second-hand equipment, particularly pipe, is seldom justified. Most floods last from seven to 12 years, and little second-hand material will last that long. Its use is false economy, except in the case of machinery known to be in excellent physical shape.

Water plants can be either the open or closed system types. The authors favor the open system, including aerators for both make-up and return waters; large detention ponds, where adequate chemical treatment can be accomplished; and open type visible filters, where the filtering medium can be examined daily. There is no denying that the closed system is cheaper, but as the condition of the injection water is the very heart of the operation, it must be kept under absolute control. Few closed systems lend themselves to such control. The cost of this open type of plant varies considerably. As the authors do not like to attempt to flood less than 300 productive acres, most of our plants are built for an ultimate capacity of approximately 6,000 B/D and contain two pumps and motors with four 8 ft x 10 ft redwood filters charged with the usual gravel and ground anthracite coal. Detention ponds are equipped with the required chemical feeders and have capacities ranging from 10,000 to 25,000 bbl. All plants are electrified with automatic controls. Exclusive of the supply well or other raw water source, the cost of such a plant will range from $50,000 to $60,000.

It has been the authors' experience that reduction of plant capacity from 6,000 to 4,000 B/D will not save one-third of the cost. It is doubtful if the saving would exceed 10 per cent.

Regardless of the type of plant to be used, it is fairly easy to ascertain the exact cost as the kind and type of equipment required will be known in advance.

Source of water to be used for injection purposes entails another engineering and cost study. Assuming that an adequate supply of suitable water is available, the cost of procuring such water should be included in the total plant cost.

Decision to flow or pump must be made at the time that large scale development is undertaken. Development costs are obviously lower in a flowing flood, but there are so many factors favoring pumping that the authors have abandoned any further consideration of flowing. This decision was influenced by the belief that

recoveries under flowing will be less and most assuredly pay out will be longer delayed. Ultimate profits, determined only after such longer pay out (which must be discounted to present worth), seem to condemn flowing. The subject is just another point on which waterflood operators continue to disagree.

In general then, development costs can be reasonably accurately determined after the final program has been decided upon. Cost of materials is largely fixed, labor rates are fairly well established and contract drilling charges are known.

Operating Costs

This category of costs requires more complex study because of the tremendous number of variables involved. Aside from supervision, direct labor costs, and overhead, all of which can be quite accurately calculated, consideration must be given to the following:

1. Water Treatment. This varies not only from field to field, but from day to day, particularly if return water is mixed with make-up water. Cost of treated and pressured water can range from 1¼ cents per bbl to 3 or even 4 cents per bbl, depending upon the chemical treatment required and the cost of producing the make-up water at the surface. The average cost should not exceed 2 cents per bbl.

2. Return Water. Production of ever increasing quantities of return water during the life of the flood makes it imperative to provide for disposal or re-use of such water. Attempts at disposal have generally proven unsatisfactory and costly, principally due to the amount of water which ultimately must be handled. Hence, the re-use of such water, despite some increase in treatment costs, is recommended. Separate chemical treatment of make-up water and of return water is coming into favor because of the resultant closer control over the combined waters. Such costs constitute a substantial portion of the cost of "treated and pressured water."

3. Corrosion. This is a very serious problem in any water flood, and experience has taught the authors to use materials which will resist or even overcome corrosion. These are such items as plastic pipe for low pressure lines, plastic or cement lined pipe for input strings, high pressure water lines, and flow lines. In particular, the authors try to eliminate the use of dissimilar metals in contact with corrosive waters. Material replacements have a vital bearing on operating costs. In this connection, the use of second-hand materials, particularly pipe, has an equally adverse bearing on these costs.

While anti-corrosion equipment adds to development costs, the reduction in operating costs is sufficient to justify extensive use of such materials.

4. Oil Treatment. Water flooding has a tendency to increase oil treatment problems and wherever this occurs, it adds to operating costs.

5. Cleaning out. In computing operating costs, provisions must be made for cleaning out both inputs and producers from time to time. Obviously, the inputs are the most important. The sand face must be kept absolutely clean, as, even under the best of chemical treatments and the use of corrosion preventatives, it clogs up fast enough. Washing, acidizing, and the use of special chemicals for this purpose can maintain input rates at reasonable levels. One cannot ignore the truth of the axiom, "If you cannot get the water in, you cannot get the oil out."

6. Shooting. Some horizons lend themselves to shooting with nitroglycerin. In other formations, it not only does little good, but can be hazardous and costly. Experience would seem to be the best teacher, as few of the "experts" are in agreement on this problem. The cost of the shot, added to cost of cleaning out after shot, should be balanced against the cost of drilling a larger hole through the sand. Personally, in Texas the authors favor the use of a large hole (minimum 6⅞ in) through the porous portion of the sand body and avoid the use of nitroglycerin or acid whenever possible. This comparison does not tell the final story, as shooting does cause added subsequent cleanouts, and these additional costs must be made a part of any shooting study. The cost of cleaning out both inputs and producers over the life of the flood is substantial, and provision must be made for it.

7. Selective Plugging. Due to recent developments this is now yielding excellent results with but little addition to operating costs. Depending on materials and equipment used, such charges can be as low as $25 per well but do at times run as much as $500 per treatment. Some provision for this should definitely be included in an operating cost survey.

8. Reopening and Replugging Abandoned Wells. Generally written off as an operating expense, this can be very costly, particularly in the very old fields where location of such wells is unknown and there remains no surface evidence by which they can be found. Merely locating these old wells can be expensive and when an old well is reopened, one is indeed fortunate not to encounter iron in the hole. Small portable rotaries have proven their worth in this work. The cost of this work is of such magnitude that careful estimates are essential.

9. Hydraulic Fractures. Where man-made fractures caused by modern fracturing methods have been employed to create channels, it is obvious that some allowance in operating cost must be made for the necessary remedial work. Squeeze cementing or selective plugging often is the only solution and those costs can be high.

In general, the majority of floods to date have involved very old properties, and operating losses on such properties during the early life are almost inevitable. Seldom are these wiped out until the flood has actually proven successful, a matter of nine months to three years. Actual operating costs often range from $3/bbl (early life) down to 40 cents to 50 cents (at peak production) and back to $2 as the economic limit is approached. Over-all operating costs over the life of the flood should range between 60 cents and $1/bbl. Any figure between 60 cents and 75 cents per bbl would be considered satisfactory.

Strangely enough, an operating expense curve, plotted against the production curve, seldom reaches its low point simultaneously with the zenith of the production curve. The operating cost curve generally continues its downward trend for a number of months, even as much as a year after peak income has been reached, and then bends upward until all development work has ceased. Thereafter, following a short dip, it resumes its upward trend at an accelerated pace. At this point, disregarding any upward trend in direct labor costs, corrosion takes charge and repairs and replacements further bend the curve upward toward that point of vanishing returns — a new economic limit.

Up to this point, discussion has been confined to direct revenue vs direct costs, both stemming from the basic engineering investigation. However, there are al-

ways certain intangible, indirect or even hidden factors which greatly influence success or failure of a flood. Some of these are particularly important:

Intangible Development Costs and Taxes

Intangible development costs common to all drilling operations take on added significance in a water flood. The ratio of intangibles (normally written off as an expense) to material used (subject to depreciation only) is considerably higher in a water flood than in ordinary primary operations. At the outset of large scale development under water flooding, the ratio is about 40 per cent intangibles to 60 per cent materials, due principally to the high investment cost in the water plant and water supply. As development progresses, it becomes 50-50. By the time that the property has been fully developed, the ratio passes the 60-40 mark. While intangible development write-offs are not particularly essential in the first few years, they can offset company profits elsewhere; however, the change in ratio cited above happens to come when it is most needed, namely, when production is rising rapidly, has reached its peak, or has just started on the decline.

The saving in taxes is obvious.

Experience

There is no substitute for experience. It would be possible to cite many mistakes due to inexperience that have directly caused failures or, at least, materially reduced ultimate profits.

One simple case history involving a flowing flood clearly demonstrates the detrimental effects of lack of experience. When this flood was started in Nov., 1936, it was not known that fresh water coming in contact with bentonitic cementing material in the sand itself would cause swelling to the point where injection rates would be seriously impaired, whereas, salt water, if devoid of injurious salts, would shrink such cementing material and permit more rapid injection at lower pressures. With ample fresh water available from a nearby city reservoir, the plant was designed to use this water. Initial injection rates seemed satisfactory, but it was soon apparent, from the injection pressures required, that satisfactory input rates could not be maintained. Although only 700 ft deep, plant pressure in excess of 800 psi was eventually required to maintain even subadequate rates of injection, and subsequent breakthroughs were not uncommon. Disregarding breakthroughs, few of the input wells took this fresh water at reasonable rates, thus prolonging peak production, pay out, and the ultimate life of the flood. The first upturn in production occurred in Feb., 1938, and strangely enough in Nov., 1942, both peak production and pay out occurred, six full years after the flood was started.

This basic mistake showed up in other ways. While the water used was actually city drinking water, and was further treated and filtered at the injection plant, corrosion was excessive. Materials started to fail before 1946. By 1950, in spite of the fact that this flood was still producing a substantial amount of oil and return water was not excessive, labor and materials constantly required to fix leaks resulted in such high operating costs that the property has been operated since that time, for all practical purposes, for the benefit of employees and royalty owners alone. Seven employees were required where two or three should have been ample. More rapid injection rates would doubtless have recovered as much, if not more, oil in faster time. The truth of the matter is that the flood outlasted the material. Effort was made to correct this trouble by shifting to salt water sometime during 1949, but swelling had already taken place and it was too late. While the flood was an economic success, net profits should have been far greater.

Design of plants, well completion practices, water treatment, and engineering solution of daily problems, as they arise, are all part of this category, called "experience." In the authors' opinion, it is absolutely essential to have trained personnel live with a water flood in order to correct mistakes before they cause damage. Experienced supervisors are expensive, but they pay dividends throughout the life of the flood. Lack of cooperation between engineers and field personnel can readily lead to economic defeat. The authors feel justified in stating that problems that arise daily must be solved on the ground before impairment takes place.

On the other hand, major companies often have the "know how" through large and excellent engineering staffs, but they are handicapped by high overhead and high labor costs. A case in point has to do with one of the most "successful" floods in the Mid-Continent area, where one of the vice-presidents is reported to have stated, "We had a wonderful flood; we got more oil out of that pool than we ever expected, but we never made a dime."

At the other extreme is another case in point. One Texas man, without experience, engineering, or adequate capital, tried to put on a "poor boy flood." He had an excellent property and had every reason to expect a recovery from 3,500 to 4,000 bbl per acre. Because it was cheap, he made the mistake of injecting "gyp" water at ever increasing pressures. He has unfortunately ruined his field; but, by the same token, he thinks that he had wonderful success because he recovered an additional 800 bbl per acre before abandonment. To be sure, he made a profit, but 10 times the profit was available to him, had he had proper engineering experience and adequate working capital.

The writers naturally encounter many operators who prefer to do their own flooding. When one realizes that probably seven out of every 10 floods are failures for one reason or another, and that perhaps only two out of the 10 could be excused for completely hidden factors, one has to seek the basic causes for such a high percentage of failures. Broadly speaking, these can be attributed to one or more of the following: (1) improper engineering, (2) lack of experience, or (3) shortage of adequate working capital. These factors lie at the bottom of almost every uneconomical waterflood.

Conclusion

It should be obvious that the first phase in any waterflood project should be complete engineering study and that evaluation of the different factors which would influence costs must be made before any water flood is undertaken. Many of these factors are fixed, unchangeable; others can sometimes be varied sufficiently to convert a sound engineering project into a sound economic one.

Successful waterflooding is entirely dependent upon the three basic factors: engineering, experience, and economics. ★★★

WATER SOURCE and REQUIREMENTS

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Introduction

Poor selection of a water source and a miscalculation of the water requirements can affect adversely the economics of a potentially successful flood. A methodical examination of the sources, selection of the best one available, and application of engineering principles to the development of that source mean cheaper production of each barrel of waterflood oil.

Following is the preferred order for approaching these basic problems which must be solved early in the launching of a waterflood program: (1) determine the requirements as accurately as data permit; (2) survey all possible water sources with special attention to the quantitative satisfaction of the requirements; and (3) develop the selected source in the most economical manner permitted by good engineering practice.

Waterflood Requirements

Daily Water Injection Rate

The heaviest drain on the make-up water source is during the fill-up period when there is no return water and the desired unit daily injection rate is as much as twice that needed after fill-up. The maximum daily total injection rate usually is tempered somewhat by progressive development of the flood acreage.

Empirical relationships established during 18 years' experience with injection projects throughout the country are the bases for the following general requirements. During the initial or fill-up period of injection into a depleted reservoir, a unit rate of between 1 and 2 B/D/acre-ft is desirable. This normally will result in increased oil production within six to nine months without adversely affecting the ultimate oil recovery. After fill-up has been achieved, the injection rate should be maintained at about 1 B/D/acre-ft and at not less than ½ B/D/acre-ft. Flood pattern, well spacing, and injection pressures should be designed to meet these requirements.

For depleted reservoirs in which there is gas sand in the top of the sand section, together with basal water sand, the water requirements normally will be several times that for an oil sand section alone. The gas sand must be filled with water in order to prevent, as much as possible, migration and loss of oil into such sand. Fill-up requirements for the gas sand normally will be approximately three to four times that of the oil sand on an acre-foot basis. Similarly, allowance should be made for water movement into the basal water sand even though such sand is not exposed in the injection wells. Unit fill-up in the water sand usually will be about the same as in the oil sand section. Unless there are competent shale or lime breaks several feet in thickness lying between the gas sand and oil sand and between the oil sand and water sand, the gas and water zones should not be neglected in estimating water requirements.

For pressure maintenance operations, daily injection rates should be at least twice the daily oil production rate and preferably at a unit rate of at least ¼ to ½ B/D/acre-ft.

Ultimate Water Requirements

The pore volume method has been found to be the simplest and best for estimating ultimate water requirements. Experience indicates a range of from 150 to 170 per cent of total pore space will be required for total flood life. Total pore space should include the pore volume of any adjacent overlying gas sand or basal water sand. Probable error using this method should be less than 15 per cent.

Establishment of a reasonable estimate of the ultimate water requirements is important inasmuch as it is a basis for determining the amount of make-up water which will be required throughout the flood life. Furthermore, ultimate water requirements together with average water injection rate will serve as a basis for estimating total flood life.

Re-Cycled Water Versus Make-Up Water

The volume of return water becomes an increasingly significant percentage of the required injection rate as a flood progresses. Therefore, it is an economic necessity that the water be re-cycled unless the treating cost for the re-cycled water is higher than that of the make-up water.

If gas or water sands are not present, make-up water will comprise 40 to 50 per cent of the ultimate water requirements. If gas or water sands are present, less return water will be available, thus increasing the ultimate make-up requirement to as much as 60 to 70 per cent of the total water injected.

[1]Paper given at Secondary Recovery Symposium presented by North Texas Section of AIME and sponsored by North Texas Oil and Gas Association, Nov. 17-18, 1954.

Water Sources

There are three principal fresh water sources and two sources of salt water which can be used for flooding purposes. Fresh water supplies include surface waters, waters from alluvium beds and subsurface waters. Salt water sources include subsurface waters and the oceans. Where economics permit, salt water usually is preferred to fresh water.

Fresh Water—Surface Sources

Surface waters, including ponds, lakes, streams, and rivers have been used throughout waterflooding history and these are the sources for which competition is highest from other industries and from municipalities. Large increases in the universal demand for fresh water and prolonged drouths have resulted in water shortages which were not foreseen even 10 years ago. We may expect alleviation of the drouth, but the demand for water will surely increase. In many areas these shortages have spurred requirements for state approval of use of water supplies. Thus, if fresh water is to be used it may be necessary to obtain approval of the appropriate state agency before proceeding with development of such source. If salt water is chosen as the injection medium the question of legal approval of withdrawal usually is non-existent.

Small ponds and streams are very unreliable as a constant source of supply for all seasons of the year. Large lakes and rivers are preferred; however, these also may have limited capacity during drouth periods. One major oil company flood in Oklahoma was shut down for weeks as a result of the drouth during the past summer. When shortages appear, domestic users have first priority.

Principal disadvantages of surface sources are unreliability of quality and quantity, the high cost of treating equipment and the cost of chemicals and operation.

Fresh Water—Alluvium Beds

An improved method of using river or stream waters is to tap the alluvium beds near the river with shallow wells. Utilization of this source by some of the world's largest water floods—the Salem flood in Illinois and the Burbank and Olympic pool floods in Oklahoma—is indicative of the high productivity available. If closed systems are used, chemical treatment other than possibly a bactericide normally is not required. Filtration usually is unnecessary because of the natural filtration of the alluvium sands. Sulfate reducing bacteria, which are anaerobic in nature, can thrive within a few feet of the surface so waters from alluvium beds may be and frequently are highly contaminated with these troublesome bacteria. Control of these organisms usually costs at least 1 to 2 mills per barrel.

Quantitative reliability of this source is slightly better than the reliability of the adjacent river or stream. If the river dries up, the water table will drop steadily but the wells should provide at least a four-week supply. Qualitatively, the wells are more dependable than the direct surface sources. They are not subject to extreme turbidity changes during rainy seasons nor to the variable organic content of the surface waters.

Spacing of individual alluvium bed wells is not a critical item if the river level is high enough to provide good replenishment of the beds. Common completion practice is to set perforated casing in the sand bed using a gravel pack on the outside of the casing. Large casings are used when high productivity is desired. They may be replaced by caissons large enough to permit driving of horizontal shafts into the alluvium sands when extremely large quantities are needed. Turbine pumps, shaft driven from the surface, are suitable for this type of well.

Another method for tapping alluvium beds is to drive 2-in sand points, join them at the surface with 6-in pipe and pump the entire battery of points with one centrally located centrifugal pump on the surface. Ten to 20 points spaced 25 ft apart can be operated with one pump. Maximum permissible depth of fluid level is about 20 ft and shallower levels of 10 to 15 ft are preferred. Since the pump pulls a vacuum on the entire pipe gridwork, special care should be taken to insure air-tight joints. Entrance of small amounts of air will reduce greatly the pump efficiency and also accelerate the corrosion rate.

Principal advantages of alluvium bed sources are low development costs, low pumping costs and elimination of filtration. If bacteria are not a problem, corrosion rates should be low and chemical treatment unnecessary.

Fresh Water—Subsurface Formations

Subsurface sand or lime formations may be drilled for water production with good results in some local areas. Such formations range in depth from the surface to 1,000 ft or more and good quality water usually is produced. As in the case of the alluvium wells, closed systems are preferred, thus eliminating chemical treatment and filtration requirements. Common pipe requirements include a few feet of surface pipe and the producing string which is set either at the top of the sand or set through the sand and completed by perforating the water zone.

Completion in a single zone is much preferred; however, multi-zone completions usually are satisfactory and can be tried where the supply from a single sand is inadequate. Upon completion of the well, draw-down tests should be made by swabbing or bailing to determine the initial productivity. Optimum spacing of water supply wells varies considerably with different formations. It may vary from as little as 25 ft for sand points to as much as 1,320 ft for deep wells.

Pumping equipment may include surface driven or submersible centrifugals or rod pumps. Selection should be governed by the economics involved which are influenced by static fluid level, draw-down and the desired productivity.

Advantages of these wells include low corrosion rates and elimination of a chemical treating plant and filtration.

Salt Water—Subsurface

In many oil fields there are salt water formations either above or below the oil zone that are potential sources of water supply. The relatively shallow salt water wells are similar in most respects to the shallow fresh water wells. The wells are completed in the same manner and have the same advantage of being adaptable to closed systems.

Many areas are fortunate enough to have deeper salt water formations which have extensive areal coverage

and thicknesses up to several hundred feet. These prolific formations frequently have high static fluid levels which permit very economical operation. Reda pumps are used where pump settings below 1,000 ft and large fluid withdrawals are required. At depths less than this, operators have a choice between the submersible pump and shaft driven turbine pump. These formations usually produce waters with high mineral content with wellhead temperatures in the range of 100 to 170° F. Hydrogen sulfide may or may not be present.

Most subsurface waters can be used in closed systems without treatment or filtration. If the water contains significant amounts of hydrogen sulfide, an open system including aeration, sedimentation and filtration should be used.

Completion practices in deep supply wells vary with local conditions. Many are completed with one string of casing set and cemented at the top of the water zone. A minimum casing size of 8 in is recommended for wells where Reda deep well or turbine pumps are to be used in order to permit running of the largest pump.

Examples of these prolific formations are the Arbuckle and Mississippi limestones in Kansas and Oklahoma, the Ellenberger lime in Texas, the Tar Springs in Illinois and the Madison lime in Wyoming. Although drilling and completion costs of the deep supply wells are high, perhaps $35,000 to $100,000, they frequently are the most economical source of large volumes of water because of the small fluid level draw-down from a high hydrostatic level.

Advantages of the deep wells include adaptability to closed systems, high, reliable productivity, the compatibility advantages of salt water with the oil sand and, where a high hydrostatic fluid level is found, relatively low pumping costs.

Salt Water—Ocean

Use of ocean water for injection purposes naturally is confined to the coastal regions. Closed systems are preferred, using shallow wells on the shore as the source of supply. A moderately high corrosion rate should be expected probably requiring use of a corrosion inhibitor. Bacteria contamination may be high enough to require a bactericide.

Advantages of ocean water supply include an inexhaustible source and low development and pumping costs.

Salt Water—Return Water

As previously stated, the total return water volume during the life of a flood will comprise some 30 to 60 per cent of the total injection requirements. If the water cost of a flood is one-fourth of the total development and operating cost, utilization of the return water will save approximately 8 to 15 per cent of the total flood cost.

In open systems, return water nearly always is added to the make-up water and re-cycled. Mixing of the waters in a pond or settling tank permits satisfactory precipitation and sedimentation of incompatible constituents. In closed systems, compatibility of the return and make-up waters is more critical but they can be mixed satisfactorily in the majority of cases.

Complete analysis of each water should be made and special attention given to detection of any of the following common combinations of ions which may precipitate upon mixing: barium and sulfate, calcium and sulfate, calcium and carbonate, iron and sulfide, and iron and oxygen.

The sulfate precipitates cause the most serious damage to injection wells because they are insoluble in common solvents or acids and require mechanical removal. Calcium carbonate and the iron compounds are more receptive to removal with acid. Empirical solubility curves are of considerable value in predicting the probability of sulfate precipitation.

Presence of barium or calcium in one of the waters and sulfate in the other does not necessarily preclude mixing of the waters in a closed system. Sequestration with a polyphosphate usually permits satisfactory use of the waters. Make-up water sources or the use of return waters sometimes are rejected unnecessarily because of recommendations by chemists who are unfamiliar with waterflood work. Operators oftentimes are inclined to overtreat waters, justifying the expenditures as insurance. This procedure not only is poor engineering but also poor business as is exemplified by some elaborate open systems costing more than $50,000 which have been by-passed and abandoned in favor of a relatively simple closed system.

An operator can convert from a closed to an open system with no appreciable loss of investment, but conversion from an open to a closed system will cause considerable financial loss. Where installation of a closed system is questionable, it often is advisable to take a calculated risk with a closed system. This is especially applicable to pilot flood operations where the cost of cleaning out or acidizing a few injection wells is minor as compared to the money lost if a chemical treating plant is installed unnecessarily.

It is well known that return waters contain small suspended particles of oil if the water is not filtered. Concentrations up to 10 ppm are not uncommon. Although presence of this oil in the injection water causes some anxiety with some operations, vast field experience indicates that it is not deleterious to most Mid-Continent oil sands.

Summary

A shortage of surface waters for water flooding exists in many potential waterflood areas. Aggravation rather than alleviation of the shortage is anticipated through the coming years. Most prospective waterflood areas have alternative sources in the form of deep subsurface fresh or salt water bearing formations. Development of subsurface water sources is preferred economically in many cases to surface sources.

Calculation of the water requirements for a prospective flood should include the daily total injection rate and the ultimate volume needed. All possible water sources should be examined to determine which have adequate supply to satisfy these requirements. Cost comparisons of each adequate supply should be used in selecting the most economical source and type of system. Where the use of a closed system is questionable, it still is oftentimes advisable first to take the calculated risk with a closed system, especially in pilot flood operations. Then, if necessary, the installation can be modified and expanded to an open system.

Experience indicates that, if conditions are favorable, a closed system is preferred to an open system and subsurface salt waters are preferred to fresh waters as the make-up source. ★★★

WELL COMPLETIONS for WATERFLOOD OPERATIONS

MARSH S. WATSON, JR.
TED G. WARD, JR.
JUNIOR MEMBERS AIME
GEORGE L. BUCKLES

BUCKLES AND HOSTETLER
MONAHANS, TEX.

Abstract

Reservoir conditions in Permian sand fields of West Texas present problems in waterflood operations unique to that area. These are caused by upper water-bearing formations; a series of sand lenses in the producing zone separated by shale, sandy shale and dolomite stringers and gas sands above the producing oil zones. In some fields bottom-hole water is present in the down dip area in the principal oil-producing zone. It is pointed out that the most satisfactory methods used to overcome these problems could apply to any area where an open hole completion would be possible.

The paper presents a discussion of current completion practices for injection and producing wells. The methods by which properly completed wells help to solve the problems of thief zones, injection rates, maintaining properly treated water, and isolation of the sands to be flooded are presented.

A method for completion of cable tool holes, where the operator may chip core and shoot the producing zone before running casing is discussed in detail.

Introduction

The essence of water flooding is to inject water continuously into the pore spaces of an oil reservoir at a rate that will result in the production of the maximum amount of commercially recoverable oil. Any mechanical, chemical, or biological processes that assist or detract from this endeavor are of vital importance.

In its simplest aspect the problem then resolves itself into injecting the most suitable water available into an oil bearing formation at the right pressure. This involves spacing, pattern, water treating and well completions.

Pore spaces refer to any openings through which fluid could pass.

The scope of this paper concerns itself with well completions.

Injection well completion is the most critical factor to waterflooding success. This for the simple reason that the injection well is the sole medium for directing the water to its function. In like manner producing wells must be completed so that all waterflood oil can be produced It is an economic waste to continually attempt to work over a completed injection well, and it is a hazard to try to solve all problems by increasing injection pressures.

Paper given at Secondary Recovery Symposium presented by the North Texas Section of AIME and sponsored by North Texas Oil and Gas Association, Nov. 17-18, 1954.

Most of the information contained in this paper refers to problems encountered in flooding the Yates sands in the Permian Basin of West Texas, but solutions should apply in any area.

The Injection Well

Function of An Injection Well

It must be understood that water serves no useful purpose unless it assists in producing oil. An input well then has a twofold function. It enables water to enter pore spaces containing oil which forces the oil to migrate to other wells where it can be produced. It also prevents oil from entering other pore spaces where it could conceivably never be produced.

Therefore, any well completion that would exclude water from pore spaces containing oil or that would force oil into pore spaces that have no relief in a producing well has failed to perform its function.

Any water that by-passes pore spaces containing oil and is produced is not only an economic waste in itself but could prevent normal waterflood oil from being produced.

Some Beneficial Features

Thief Zones

Thief zones would include any pore spaces that could receive injected water that would not result in the recovery of oil. Another type would be pore spaces into which oil could migrate without being produced. Fortunately these are generally above or below the oil producing horizons. An example of those above the oil producing zones would be a gas sand that could take large quantities of water without producing any oil and an example of those below would be a water bearing formation that could do the same. It is imperative that such zones be isolated from receiving water or oil.

Surface Area Exposed

Under the most favorable conditions it is practically impossible to have perfect water. The best water will from time to time contain some suspended solids which will tend to form an impermeable layer on the face of the exposed pay formation. It is therefore desirable to have as much wellbore area of the formation exposed as possible. The most practical method to accomplish this is a large diameter hole.

Dead Fluid Spaces

Bacteria is now being recognized as the hazard it has always been in water flooding. It creates severe corrosion and formation plugging problems. Any spaces

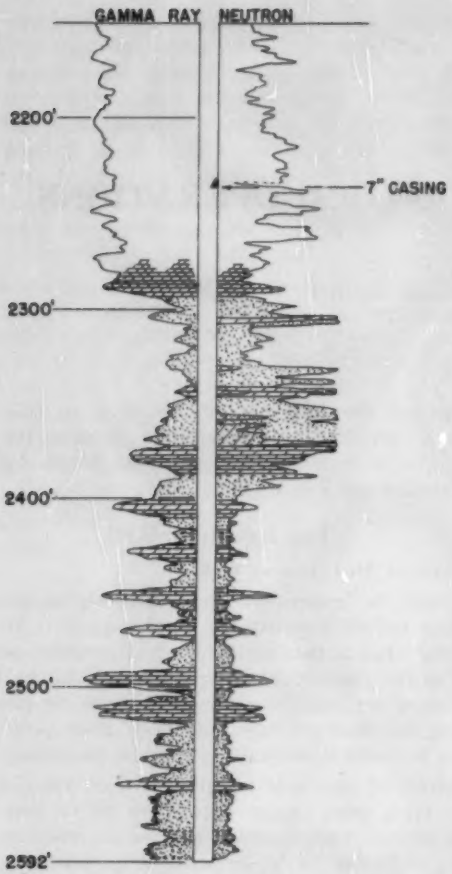

Fig. 1—A typical Yates section in the South Ward field.
The top of the Yates is at the base of the Tansil at 2,292 ft and the bottom is just below the total depth. The section from the top of the Yates to 2,400 ft in certain parts of the field is gas bearing. The principal oil producing zone is from 2,517 ft to 2,592 ft. The drawing was made from a gamma ray-neutron log of a cored well.

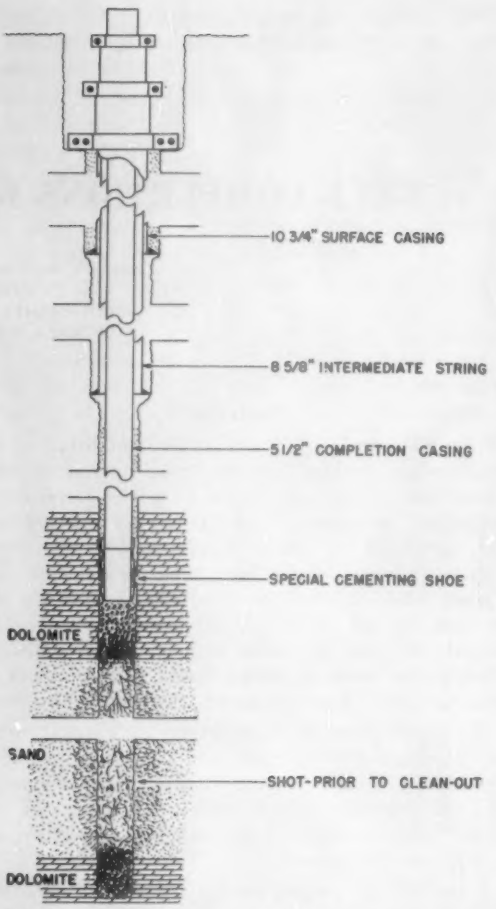

Fig. 2 — The typical completion procedure prior to cleaning out and running tubing.
The well has been shot, and casing run and cemented. After the 8⅝-in intermediate casing has been stripped over the 5½-in casing, the casing clamps on the top of the 10¾-in casing are removed and the 5½-in is supported by a slip type casing support.

in the entire water system and especially in the injection wellbore where water does not have free movement creates an excellent breeding place for bacteria. An example of this would be open hole below the producing zone in an impermeable formation.

It would be desirable then to have the input well equipped to circulate fluid to bottom at any time without the necessity of running a temporary inner string of pipe or moving it in a cleanout rig.

An arrangement of this kind would also facilitate acidizing sections that were plugged. Normally acid could not reach these sections because there would be no movement of fluid into the plugged area. In a similar manner any portion of the wellbore could be slugged with a bactericide.

Isolation of Unproductive Zones

It would be advantageous to expose only the productive sections in the input well if this could be accomplished without eliminating other more beneficial features.

The Producing Well

An open hole producing well completion has proved the most satisfactory in Permian Basin water floods. Certain quantities of fine sand are produced with the oil, but this is common in any completion method, especially during the early stages of flood operation.

It is often necessary to clean out producing wells after the initial increase in production, and an open hole completion facilitates access without additional preparatory work.

Calcium sulfate scaling is common in the producing wellbore and in some instances perforated liners have been cemented by the sulfate deposition to the extent removal was a long and expensive operation.

Current Well Completion Practices

The current method of well completion, as used by the writers, is the culmination of a study of well performances and the effort to combine as many beneficial features as possible in one operation.

Cable tools are used from top to bottom except in rare instances where upper unconsolidated sands cause too much trouble in this type of drilling. Cable tool completion is preferable, and the over-all cost is more if both rotary and cable tools are used on the same well.

Upper water sands are protected by cementing a string of 10¾-in casing to the surface. This is set in the first good body of red bed shale encountered below shallow water bearing sands. This red bed may be encountered from 60 ft to 450 ft below the surface.

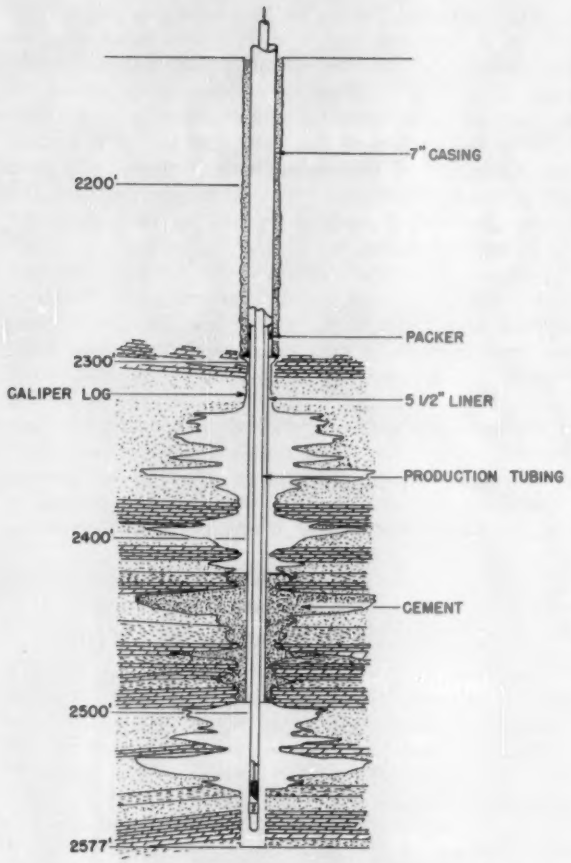

Fig. 3—A recompletion of an old producing well where the 7-in casing had been set above the upper Yates gas sands.

This completion procedure allows the well to be used either as a production or injection well. The drawing was made from a caliper survey and the cement fill-up was measured by a temperature survey. The formations were filled in from a gamma ray-neutron log.

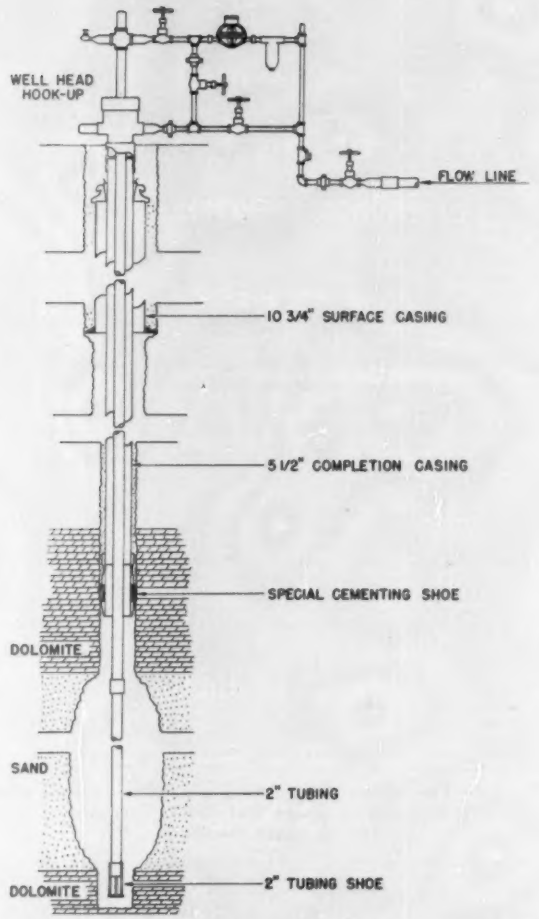

Fig. 4 — The final completion of a water injection well with the meter run and wellhead hookup.

The Rustler formation is encountered from 550 ft to 1,450 ft, depending upon which part of the Permian Basin the operations are to be conducted. It generally consists of a very permeable lime and varies from 150 ft to 200 ft in thickness. Because of its water bearing characteristic, it is necessary to set an intermediate string of 8⅝-in casing through it. This string seals off all upper water bearing formations and facilitates drilling to bottom without an additional string of pipe. The 8⅝-in is not cemented and is pulled after the long string is run. In the event upper water cannot be shut off, or water below the Rustler is encountered, it is still possible to run 7-in casing as another intermediate string.

The formations between the Rustler and the Yates are the Salado, composed mostly of salt and anhydrite, and the Tansil which is a dense dolomite.

The top of the Yates is encountered from 1,500 ft to 2,500 ft depending again upon the location. It is roughly 300 ft thick and consists of a series of sand lenses separated by shales, sandy shales and dense dolomite stringers. The net pay sand varies from a few feet to as much as 60 ft. In general the first sands encountered carry gas and there are a few local gas caps present in the principal producing zone. In some areas bottom hole water is present in the down dip areas of the lowest oil producing zone. In other areas the first sands encountered are the oil producing zones and the lower sands carry only water. In a few instances the shales separating sand lenses contain bentonitic material.

In any event careful completion practices are of the utmost importance. The method most favored by the writers is to chip core the entire Yates section to be flooded. In this manner the gas-oil and water-oil contacts can be ascertained in addition to getting normal core information. In general, where a local gas cap migrates down dip into an oil zone, it is left open in the injection well completion to prevent oil from being forced into the gas cap. In like manner water zones are left open if they change to oil zones up dip.

After chip coring operations are completed the entire pay section is shot before running casing. Liquid nitroglycerin is generally used with a minimum of 2 quarts to each foot. Sometimes the tighter portions are shot heavier. The shooting is principally to enlarge the size of the hole. The shot is tamped with about 50 ft of gravel. After shooting, the gravel is cleaned out to the desired casing seat and 5½-in casing is set and cemented, using a special cementing shoe with packer to prevent cement contamination below the shoe. The hole is then cleaned out thoroughly to bottom through the casing.

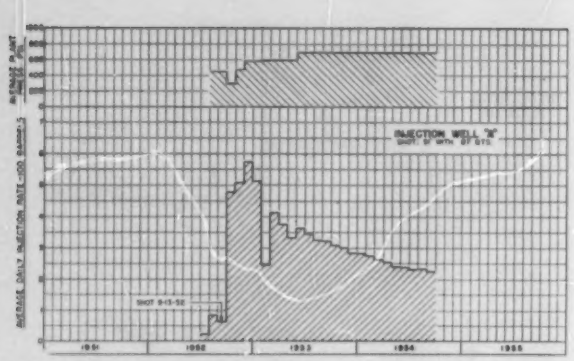

Fig. 5 — The effect of shooting a water injection well after water had been injected for 2½ months prior to shooting.

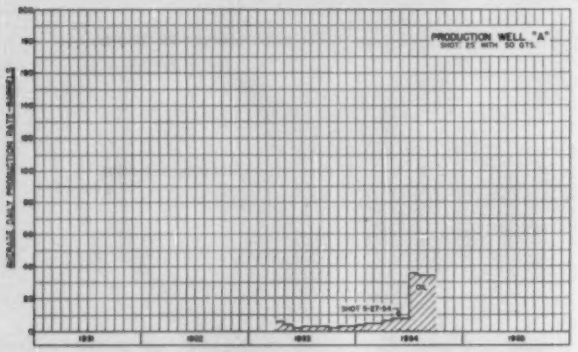

Fig. 6 — The effect of shooting a producing well after it had shown a slow but steady increase due to water flooding.

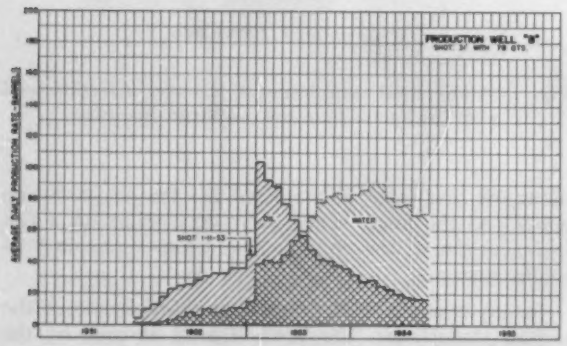

Fig. 7 — An old producing well that had been shot heavily in 1936.

Increase by water flooding started in Dec., 1951. The production had leveled off by the latter part of Dec., 1952. The well was then re-shot Jan. 11, 1953.

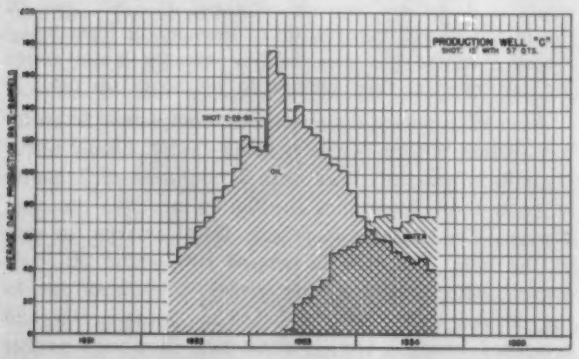

Fig. 8 — Performance of a newly drilled producing well, which was allowed to peak and then start to decline under normal waterflood operation before the well had been shot. The effect of the delayed shot is evident.

After cleanout a string of 2-in tubing is run to bottom. It is equipped with a special shop made shoe to prevent plugging of the tubing while running in the hole. This shoe is made by welding three pieces of sucker rod to a coupling and welding a ¼-in steel plate to the bottom of the rods. The tubing is packed off at the top of the casing with a regular slip type tubing head. The meter run is connected to both the tubing and casing with a by-pass to the casing for backwashing volume.

Injection is started through the tubing, with the casing left open until the well pressures up. Water is allowed to run out at the casing head until it is clean and then injection is directed through the casing only. This is for the purpose of avoiding any dead water spaces in the system. At periodic intervals the tubing is flushed while injecting through the casing to clean the well to bottom. Thus the well can be kept clean of cavings without interrupting injection or moving in a clean-out rig. Also the well can be acidized or slugged with a bactericide in any portion of the well-bore through the tubing.

Producing wells are completed in the same manner except that a pumping string of tubing is used.

Conversion of Old Producing Wells

In event the original casing string was set low enough to isolate the upper gas sands, completions are made in the same manner as newly drilled wells.

In many instances the original casing was set too high. In that event it is the practice of the writers to cement a blank 5½-in liner at the top of the zone to be flooded and seal off at the bottom of the 7-in with a packer.

Where the original 7-in casing had not been cemented, satisfactory completions have been made by cementing a 5½-in blank liner below and up into the 7-in about 50 ft.

If the original 7-in casing leaked or was considered too weak to use as an injection string, it is the practice of the writers to run a full 5½-in inner string and cement with a special cementing shoe below the bottom of the 7-in.

In any of these conversions tubing is run to bottom and packed off at the top of the casing for input wells and the hole is left open in producing wells.

Other Completion Methods

Rotary Completions

Some wells have been drilled with rotary tools, setting and cementing casing to bottom. The pay zones have been selectively perforated. This method results in a decided restriction in area of formation exposed. Experience has shown that plugging is rapid and continuous. In order to maintain satisfactory rates, pressures are required to the extent of breaking the formation down. This invariably results in by-passing and the unnecessary handling of excessive quantities of water.

In some areas shale conditions between productive zones could preclude any other method of completion.

Gravel Packed Completions

Many of the old producing wells had been shot through most of the Yates section, including upper gas sands. No packer seat was available between the oil and gas sands. Many very successful completions were made by gravel packing a string of perforated tubing through the oil zones and cementing at the top of the gravel. The principal defect in this method are the problems and cost of any future remedial work. ★★★

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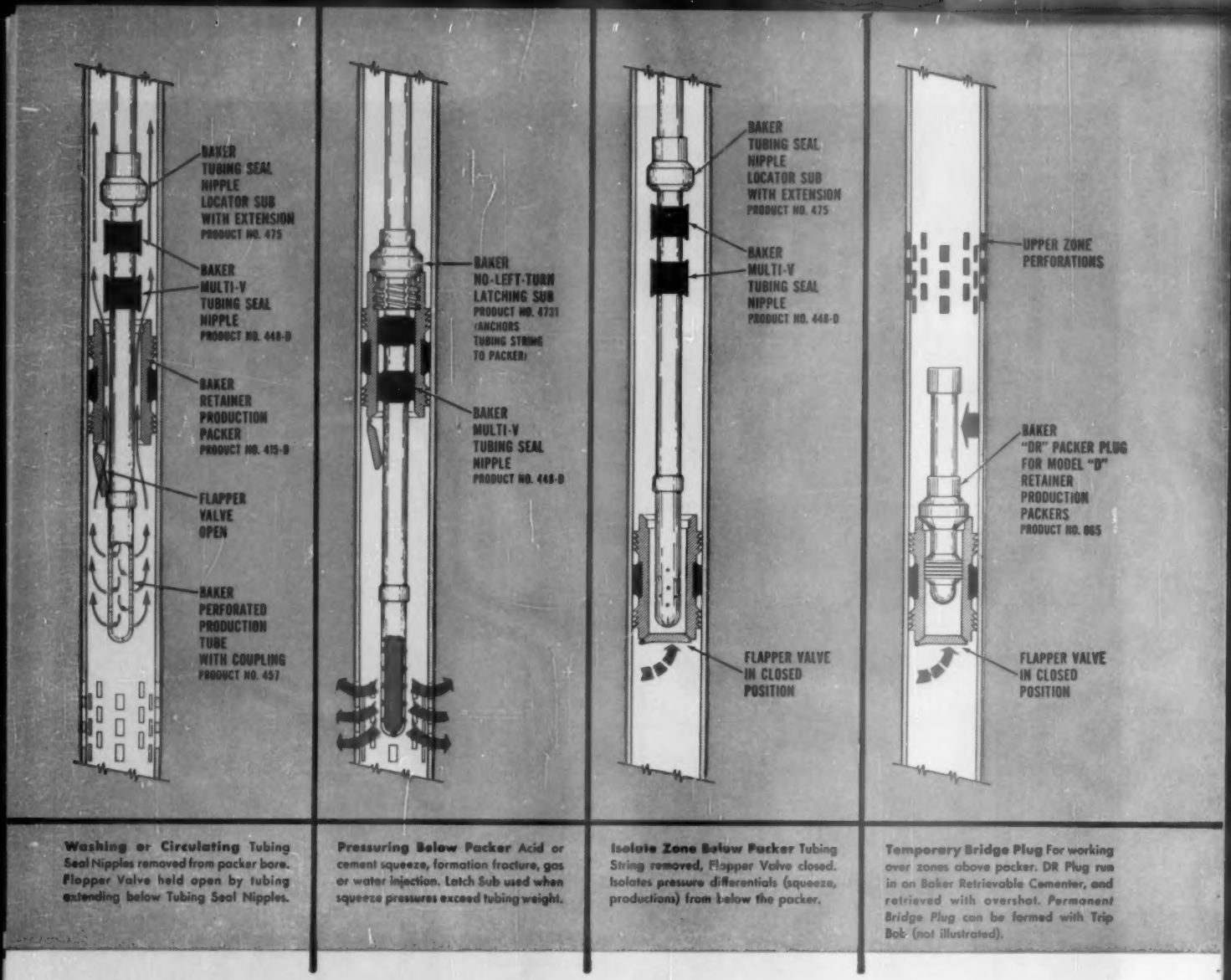
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IMPORTANT FACTS

Baker Packers are used in a majority of installations where conditions of extreme pressure, temperature, or depth are present. Baker Packers also dominate Dual Zone installations, particularly those involving two-packer, crossed-flow arrangements.

BUT IT IS ALSO TRUE that *more* Baker Packers are used for *simple single zone* completions than for *any other type of completion*, and that *most* Baker Dual Zone installations employ *only one* packer.

Ask any Baker representative, or office, for complete details, as well as your copy of the recent Baker Equipment News dealing with DUAL ZONE COMPLETION PRACTICES. There is no charge, and no obligation, for specific recommendations and completion planning advice available from Baker Technical Advisers. Why not be prepared for your next completion?

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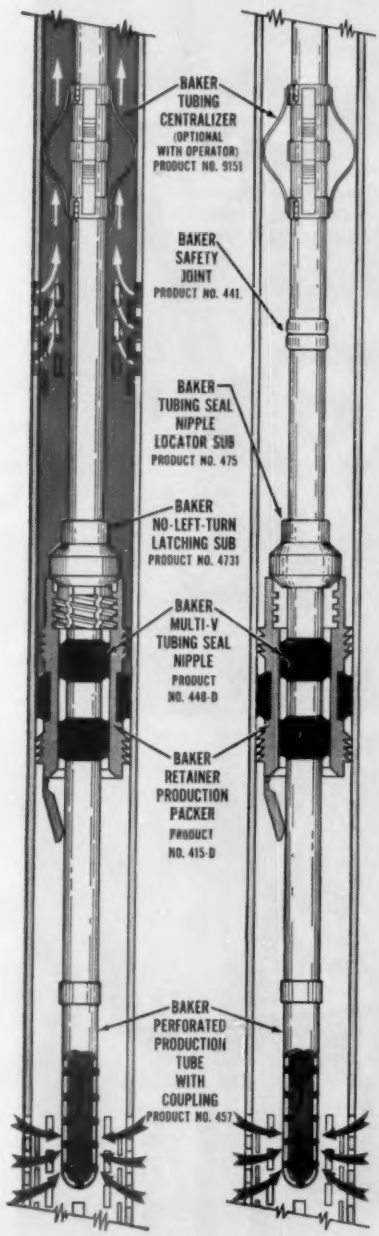
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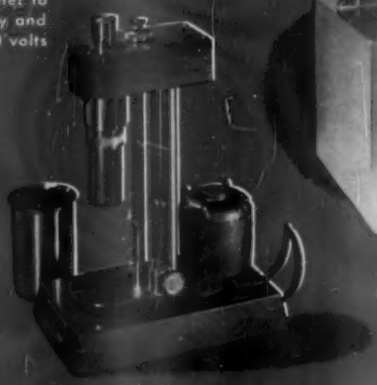

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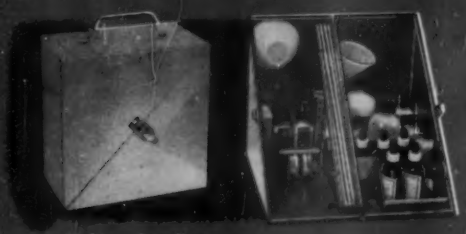

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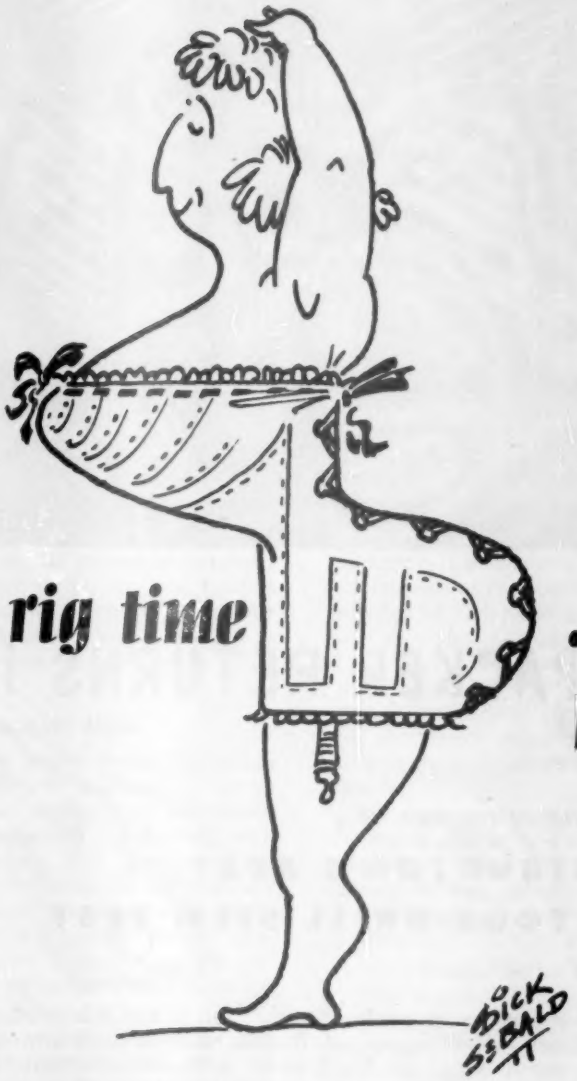

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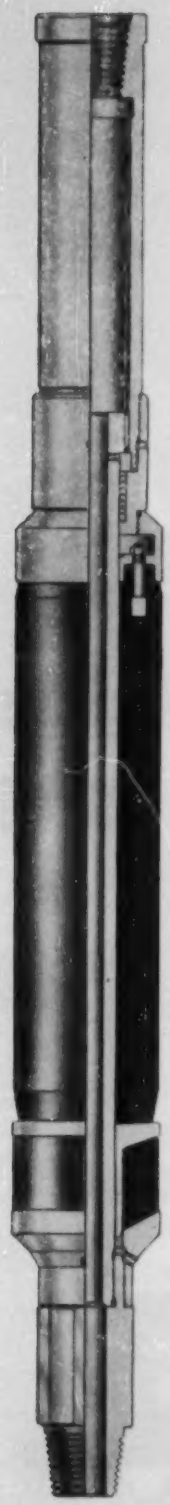

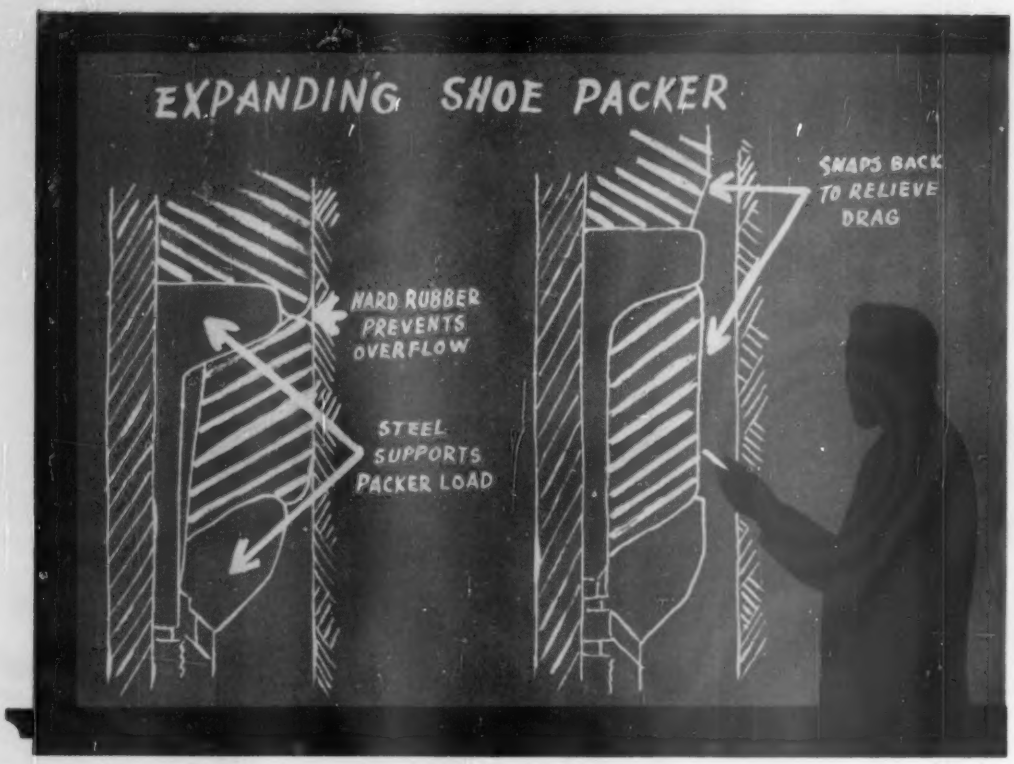

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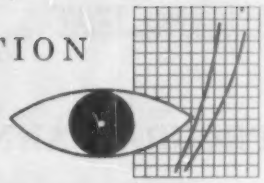

JOE B. ALFORD

EXECUTIVE SECRETARY,
PETROLEUM BRANCH, AIME

Telling the Story of Petroleum Engineering

Soon after joining the staff of the Petroleum Branch in Jan., 1949, we began to realize that petroleum engineering was not what we had previously thought it to be. As our knowledge of the profession and industry widened, an awareness developed that the contribution being made by petroleum engineering to the nation's welfare is of sizeable magnitude and significance. Then another recognition came: *that the general public has little conception of this contribution and its value to society*. Further, there are segments of the oil industry that do not fully understand the function of petroleum engineering in oil recovery.

Although we could realize the import of these facts, we could not place them in clear perspective until time brought a better understanding. Then came the feeling that we should do something to make the story of petroleum engineering more widely known. Why? First, to raise the stature of the petroleum engineer through increased appreciation of his services, both in the industry and out; second, to lay a foundation for attracting young men into the profession; and third, to help build a favorable attitude in the public mind toward the oil industry.

Colored Photographic Slides

We began to consider what would be the best means of telling the story of petroleum engineering. While flying over Wyoming one day in 1950, we saw below a well-defined anticline, exposed on the surface, with some formations eroded away. The thought came, "That's what we need to show what an oil reservoir would look like underground." Some months later, Richard W. French showed us a colored photo transparency of a similar formation in Wyoming. Finally, the answer came: tell the story of petroleum engineering through colored photographic slides.

In late 1951, we began to collect illustrations and pictures for the project, and this continued over the next two years, with intermittent thought devoted to the sequence in which they might be presented. In the spring of 1954, when pieces began to fall into place, we started the photography. All illustrations were placed on a light blue paper for continuity in borders and background, with the titles made from a home movie titling set. They were then photographed on color film with a Rolleiflex camera, which produces a colored transparency 2¼ in square. These were then mounted and placed in sequence for production.

The Presentation

The completed project is titled, "How Petroleum Engineering Increases Oil Recovery." It includes 45 slides grouped in three parts. The first is the fundamentals of oil with slides on: the physical forms of petroleum; the genesis of oil; porosity and permeability; anticline, fault, stratigraphic trap; geologic periods; oil basins of the United States; the Big Horn Basin of Wyoming; air view of Sheep Mountain; seismograph; and a reservior cross section. The second part is the application of petroleum engineering with slides on: the reservoir as a common source of supply; enlarged cross section of sand grains; types of pore space; displacement process; reservoir pressure; dissolved gas drive; gas cap drive; gas injection; water drive; water flooding, and four slides on the Phillips model of the Medrano field showing various fluid levels after production phases. The third part is the tools of petroleum engineering with slides on: electrical logging; core analysis; cementing; gun perforating; acidizing; hydraulic fracturing; and pumping. The conclusion is two slides on AIME organization and Petroleum Branch activities and publications, to show how the professional society for petroleum engineering functions, with a final word on the present and future potential oil supply of the United States and world.

We call the project a slide "presentation." The slides are shown through a projector while a running explanation is given by a speaker. They can be shown in 25 minutes or expanded to 45 minutes by changing the number of slides and the commentary. The slides contain only the information necessary for conveying the basic ideas, and with the accompanying explanation they can be fully understood by a person who has no knowledge of oil. Thus, the presentation is designed for completely uninformed groups, but can be adapted to fit various types of audiences in and out of the industry.

We have so far given the presentation before four luncheon club groups and two audiences of petroleum engineers' wives. The reception from all was most gratifying, and indicates that the presentation can do a great deal of good for the petroleum engineering profession.

Available to Membership for Use

The purpose in describing the presentation here is to make its availability known to the membership. The Petroleum Branch office has a complete set of the slides mounted in 3¼ x 4 lantern slide glass, with a 16 page (doubled-spaced) typed manuscript to accompany it. The whole kit can be shipped anywhere on short notice and used by any member for presentation to a local audience. All that is needed locally is a lantern slide projector and suitable screen. The kit is presently in the hands of Howard R. Lowe, chairman of the Billings Petroleum Section, and has been committed for presentation to the Wyoming Engineering Society in March, 1955.

We suggest that members actively seek the opportunity to give this presentation before local groups such as luncheon clubs, church groups, Desk & Derrick Clubs, high school students, and numerous groups in the oil industry other than production. Such local presentations can be easily executed. The contribution of petroleum engineering is great, but so far we have done little to make this fact known outside the profession. This presentation kit provides members an opportunity to help in telling the story, and the petroleum engineering profession can receive substantial benefit from this help. ★★★

February 12-17

PROGRAM ANNOUNCED for AIME ANNUAL MEETING in CHICAGO

The schedule of Petroleum Branch technical sessions and committee meetings has been announced for the AIME Annual Meeting, which will be held at the Conrad Hilton Hotel in Chicago, Feb. 12-17, 1955. Raymond B. Kelly, Sr., senior vice-president of production and exploration, The Pure Oil Co., Chicago, is general chairman for Petroleum Branch activities.

The AIME Council of Section Delegates meets at 10 a.m. on Saturday, Feb. 12. At 2 p.m. on Sunday, Feb. 13, the AIME Board of Directors will hold its meeting.

Production Review Session

Activities on the Monday, Feb. 14, schedule include the Petroleum Branch Executive Committee meeting, the AIME Welcoming Luncheon, and annual production review session.

R. B. Gilmore, of DeGolyer and MacNaughton, 1955 Petroleum Branch chairman, will preside at the open meeting of the Executive Committee at 9 a.m. on Monday in the Upper Tower. Gilmore, as chairman of the Production Review Committee, will also preside over the 2:30 p.m. session in the Upper Tower on World Oil and Gas Developments during 1954. Milton Williams of Humble, domestic vice-chairman, and A. H. Chapman of Arabian-American, foreign vice-chairman, will present reports.

Members of the Production Review Committee who prepared the reports to be presented are: A. H. Bell, Illinois State Geological Survey; Ward M. Edinger, Oklahoma City, petroleum consultant; L. W. Chasteen, Union Oil Co. of California; J. K. Wright, Jr., Jackson, Miss., petroleum consultant; John A. Murphy, Continental Oil Co.; and B. W. Allen, Ohio Oil Co.

Petroleum Branch Dinner

On Tuesday, Feb. 15, the first Petroleum Branch technical session of the meeting will begin at 9 a.m. in the Normandie Lounge of the Conrad Hilton. D. B. Meisenheimer, Shell Oil Co., Wichita Falls, and James K. Jordan, Humble, Houston, will preside. After adjourning at 12 m., the technical session will resume at 2 p.m. in Parlor A, with Herbert A. Metzger, Lane-Wells, Fort Worth, and Daniel M. Moon, Schlumberger, Mt. Vernon, Ill., presiding.

The Petroleum Branch Dinner is scheduled for Tuesday night, Feb. 15, with John R. McMillan, 1954 Petroleum Branch chairman, presiding. The social hour will begin at 6 p.m. in the Ballroom Foyer, with dinner being served at 7 p.m. in the South Ballroom. A noted industry speaker will talk on this occasion and the new Petroleum Branch officers will be installed. Dress for the dinner is informal for men, optional for ladies.

The final Petroleum Branch technical session of the meeting is set for 9:30 a.m. on Wednesday, Feb. 16. Howard R. Lowe, Lowe and Heath, Billings, and M. B. Penn, Mid-Continent Petroleum Corp., Tulsa, will preside. The AIME Annual Banquet and President's Reception will take place at 7 p.m. Wednesday.

Tuesday, Feb. 15, 9 a.m. — 12 m.

466-G

Air and Natural Gas Drilling by Rotary Method
By J. W. Hendrickson, *New York State Natural Gas Corp.*

The advent of air and natural gas drilling in the Appalachian area is discussed. The drilling and completions methods developed in other sections of the country where air and gas were used as the circulating medium were successfully adapted to the wells drilled by the New York State Natural Gas Corp. and its contractor, Delta Drilling Co., in the Benezette Oriskany gas field, Elk County, Penn. A substantial savings in both time and money resulted. Air and gas pressures, volumes of air and gas, and equipment used in this method of drilling are given.

378-G

Case History of Reservoir Performance of a Highly Volatile Type Oil Reservoir
Rex W. Woods, *Houston Consultant*

The case history of the performance of a highly volatile type oil reservoir which is now greater than 80 per cent depleted is presented. The reservoir is at a depth of approximately 8,200 ft and includes an area greater than 7,500 acres. The reservoir has been exploited by 10 wells which to date have yielded 11 million bbls of stock tank oil by pressure depletion. Reservoir pressure has declined from an original of 5,000 psi to approximately 1,350 psi. Produced GOR has increased from 3,200 to 25,000 cu ft/bbl with a corresponding increase in API gravity of the stock tank oil from 44° to 64°. Pressure and fluid data are given for different stages of depletion.

471-G

Canadian Oil at the Eighth Milestone (1947-1955)
W. O. Twaits, *Imperial Oil, Ltd.*
(No abstract available.)

470-G

Oil Operations in Eastern Montana
Jack D. Duren, *Shell Oil Co.*

A large part of one of the country's newest and most promising oil provinces, the Williston Basin, lies in eastern Montana. After a rather spectacular beginning, the prospects for substantial oil development in eastern Montana and the Williston Basin were considered by

many as very poor. This pessimistic outlook was the result of the early over optimistic and over enthusiastic publicity on the part of the industry. A more mature and substantial development is now taking place. Thousands of square miles remain to be investigated but difficult problems of weather, transportation, supply and service, and communication must be dealt with to bring the area to its proper relation to the other oil producing areas of the country. A brief review of eastern Montana markets and production forecasts is made along with a review of the petrophysical properties of some of the more important fields.

Tuesday, Feb. 15, 2 p.m. — 4 p.m.

473-G

Sweep Efficiencies of Vertically Fractured Five-Spot Patterns

Paul B. Crawford, James M. Pinson, Jack Simmons, and Bobby L. Landrum, *Texas Petroleum Research Committee*

Potentiometric model studies have been made of the effect of vertical fractures on the sweep efficiency of the five-spot pattern. All fractures originated at the well and extended out into the reservoir for various distances and orientations. The sweep efficiency was measured for cases in which only the center well was fractured, and in which the center well and a corner well were fractured. To utilize a vertically fractured well effectively, in some instances it may be desirable to use the fractured well as the center well of a five-spot pattern rather than a line drive pattern. It is concluded that each vertically fractured five-spot pattern will possibly be unique and will require an individual study to achieve maximum oil recovery.

477-G

Investigation of Various Refined Oils for Formation Fracturing

A. R. Hendrickson, G. L. Foster, and R. B. Rosene, *Dowell Incorporated*

The properties of some of the common fracturing oils, such as sand-filling rate, viscosity, and fluid loss, are a function of the three major constituents of the oil. These are asphaltic material, paraffin waxes, and a base oil of either high or low viscosity. The effect of these major constituents of the oil on properties of common fracturing oils is discussed. An ideal type of fracturing oil is concluded to be one containing neither asphalt nor waxes.

475-G

A New High Column Cementing Technique and a New Squeeze Cementing Technique Proves Successful

Charles A. Einarsen, *The Cherokee Laboratories, Inc.*

Adding graded black walnut shells to cement has resulted in much higher and cheaper cement columns behind casing. The walnut shells, because of their granular structure, high mechanical strength, and effective sealing characteristics, can seal wider fractures. Thus, they minimize cement losses and formation breakdowns and can support higher cement columns. Adding walnut shells to the last one-half or one-third of a squeeze cement slurry causes a series of formation breakdowns and a more uniform penetration of cement throughout the squeezed section. This technique reduces the number of stages, the quantity of cement, and rig time needed for a shut off.

Wednesday, Feb. 16, 9:30 a.m. — 12 m.

472-G

Temperature Surveys in Gas Producing Wells

K. S. Kunz and M. P. Tixier, *Schlumberger Well Surveying Corp.*

A method for the interpretation of temperature curves recorded in gas producing wells is described. One essential feature of the method is a simple graphical construction which conveniently reflects the amount of gas flowing from a given producing formation. This method, applied in conjunction with the Induction Log and radioactivity logs, is valuable to determine the points of entry of gas and to estimate the over-all thickness of the producing zones and their respective contributions to the total production. The method in particular is helpful in evaluating the effect of fracturing operations. An outstanding result of the application of the method is to bring to the light the relative importance of sand-shale interfaces in the production of gas. The paper is illustrated with field examples.

469-G

The Effect of the Relative Permeability Ratio, the Oil Gravity and the Solution Gas-Oil Ratio on the Primary Recovery from a Depletion Type Reservoir

J. J. Arps and T. G. Roberts, *British-American Oil Producing Co.*

This paper presents a study of the effect of the relative permeability ratio, the crude oil gravity, and the solution gas-oil ratio on the primary recovery from depletion type reservoirs. The ultimate recovery was computed for six different kinds of rock representing maximum, minimum, and average conditions for sands and sandstones, and limestone, dolomite and cherts, and 12 combinations of crude oil gravity and solution gas-oil ratio covering the range of reservoir oil-gas systems normally encountered. The results show the relative importance of these variables on the ultimate recovery. Comparison of the theoretical recovery trends with published recovery data on depletion type reservoirs indicates satisfactory agreement.

455-G

Flash Calculations as Performed on the IBM Card Programmed Calculator

Elliott I. Organick and Henry I. Meyer *United Gas Corp.*

Two machine procedures for flash calculations have been developed, and in each an International Business Machines Corp. Card Programmed Calculator prints a composite, compact, and accurate record of the entire calculation. The first procedure requires four minutes of machine time. It is for calculating optimum separator pressures and temperatures in single and in series staging of well effluent feed streams of up to 11 components. The second procedure is designed primarily for reservoir flash calculations at elevated pressures or for process calculations at very low temperatures where the equilibrium constants vary significantly with the composition of the feed stream. Up to 20 components can be handled in seven minutes of machine time.

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MEET the AUTHORS

GEORGE W. TRACY, senior research engineer with Stanolind Oil & Gas Co., received his BS degree in mathematics from the Central Missouri State Teachers College in 1942. He has done graduate work at Rolla School of Mines and universities of Missouri and Tulsa. He joined the Stanolind Production Department in 1947, shifting to the Research Department in 1950.

ALLEN H. FLAGG holds BA and MA degrees in physics from UCLA. After joining Lane-Wells in July, 1952, he worked as a geophysical engineer; then attended the Oak Ridge "Radioisotopes Techniques" course in 1953. Since that time he has worked to establish tracer surveys as a part of Lane-Wells' radioactivity logging service.

JACK P. MYERS is division sales engineer for Lane-Wells Co. in Midland. Before joining Lane-Wells in 1948, he was employed by Humble Oil & Refining Co. and Carter Oil Co. for eight years. He received a BS degree in geology from Texas Tech College in 1940.

JOHN L. P. CAMPBELL has been a sales engineer for Lane-Wells for the past 14 years and has helped exploit the various phases and methods of radioactivity well logging. The 1935 Cornell graduate has worked as a field geologist for Cities Service and Seaboard oil companies. A photograph and biographical sketch of E. S. MARDOCK of Well Surveys, Inc., was published in the September issue of JOURNAL OF PETROLEUM TECHNOLOGY.

JOHN M. TERRY is division sales engineer for Lane-Wells in Oklahoma City. He joined the company in 1941 as sales engineer in Illinois, and has worked in the North Texas and Panhandle districts. He is a 1937 petroleum engineering graduate of the University of Oklahoma.

FOREST F. CRAIG, JR., is a senior research engineer with the Production Research Division of Stanolind Oil and Gas Co. He joined Stanolind in 1951 after having received his PhD degree in chemical engineering from the University of Pittsburgh. A biographical sketch and picture of T. M. GEFFEN was published in the December issue of the JOURNAL.

(Continued on Page 41)

DEVELOPMENT of LETTER SYMBOLS LIST for RESERVOIR ENGINEERING

A part of the rapid development of petroleum and reservoir engineering that has taken place since World War II has been the need to standardize letter symbols and nomenclature for these fields as has been done in some of the older fields of engineering. Various members began to recognize the need for such standardization in the late 1940's, and there was some preliminary discussion on how it might be accomplished. In 1951, a proposed list of letter symbols was submitted to the Petroleum Branch for publication in JOURNAL OF PETROLEUM TECHNOLOGY. The feeling of the Branch management at that time was that such a list should not be published without official adoption by the Petroleum Branch. To justify such adoption, the list should be as complete and comprehensive as possible, and the indicated course was for the Petroleum Branch to develop an official list of symbols which might be adopted and used in its publications.

Richard W. French, chairman of the Petroleum Branch at that time, appointed a special committee to undertake the work of standardizing symbols and nomenclature for petroleum engineering. It was designated as the Petroleum Branch Symbols Committee and consisted of Francis Collins, chairman, Edward H. Mayer, Morris Muskat, T. A. Pollard, J. G. Roof, and E. G. Trostel. In Sept., 1952, a subcommittee was formed to develop a set of logging symbols, consisting of H. G. Doll, chairman, A. A. Perebinossoff, and Milton Williams.

After some preliminary study, the objective of the committee was limited to the development of a standard set of mathematical symbols for use in reservoir engineering equations. This was considered to be a good starting objective, and the broader work of definition of terms for petroleum engineering might come later. The committee began by securing the symbols lists then in use by several oil producing companies and then worked to standardize these lists. Initially, the Symbols Committee planned to acquaint a large number of individuals with the work in progress and solicit their opinions. A mailing list of several hundred names was actually compiled for this purpose. Before it was used, however, work progressed to the point where it appeared necessary for the Symbols Committee to develop a compromise list of symbols as a tentative proposal, because of the wide variety of possible symbols that might be used. This plan was adopted, and the work proceeded through correspondence and committee meetings.

In compromising on the choice of specific symbols, the committee adopted the following guides:

1. For quantities used also in other fields of science and engineering, symbols were taken from the published codes of the American Standards Association.

2. For quantities peculiar to reservoir engineering, most consideration was given to past usage in the published literature, particularly PETROLEUM TECHNOLOGY and JOURNAL OF PETROLEUM TECHNOLOGY. Unpublished lists given the most consideration were those obtained from large production research laboratories and the complete glossary compiled and submitted for publication by Edward H. Mayer, C. R. Dodson, and David Goodwill.

3. An effort was made to reduce the use of Greek letters.

In addition, general principles of symbol standardization were carefully considered. The general principles which accompany the symbol list below are essentially in accord with those which are repeated in each of the American Standard lists.

The Symbols Committee completed a list of Tentative Letter Symbols for Reservoir Engineering and submitted the list to the Petroleum Branch Executive Committee in Oct., 1954. The list was accompanied by a Style Guide for Petroleum Branch Publications and a Statement of Publishing Policies developed by the Branch staff. The Symbols Committee recommended that the tentative list be published in JOURNAL OF PETROLEUM TECHNOLOGY, with an explanation of procedure used in adopting the list and a request for submission of comments and suggestions by Petroleum Branch members at large during a specified time interval following publication. The Branch Executive Committee voted:

1. To approve the tentative list as submitted by the Symbols Committee.

2. To publish the list in JOURNAL OF PETROLEUM TECHNOLOGY.

3. That one year from date of publication should be allowed for alterations in the list by the Symbols Committee.

On the basis of this action, all Petroleum Branch members and interested organizations are invited to submit comments and suggestions on the Tentative List of Letter Symbols for Reservoir Engineering published in this issue of JOURNAL OF PETROLEUM TECHNOLOGY. Such comments should be addressed to:

Symbols Committee
Petroleum Branch AIME
800 Fidelity Union Building
Dallas 1, Tex.

Comments will be received until Jan. 15, 1956, when the Symbols Committee will develop a final list for submission to the Branch Executive Committee. When adopted by the Executive Committee, the final list of symbols for reservoir engineering will be published in booklet form and made available to all interested parties. All authors submitting papers to the Branch will then be requested to conform to the standard list of symbols, and all material published by the Branch will conform to it.

In the list on the following pages the symbols are in alphabetical order. Two additional arrangements are proposed for publication with the revised list, one with names of quantities in alphabetical order and one with quantities in related groups.

The logging symbols subcommittee has been working concurrently and has ready for publication a list of symbols for electric logging. ★★★

LETTER SYMBOLS for RESERVOIR ENGINEERING

General Principles of Letter Symbol Standardization

1. Letter Symbols. A letter symbol for a physical quantity is a single letter intended primarily for use in mathematical expressions. The same letter symbol should be used consistently for the same generic quantity, special values or units being indicated by subscripts or superscripts.

2. General Requirements for Printed Symbols.

(a) STANDARDIZATION. Authors are urged to use the symbols in this and other standard lists and to conform to these general principles. An author should include a list of symbols or should refer to a standard list. An author may need symbols not included in standard lists. He should then select the simplest and most suggestive symbols that he can without conflicting with standard lists in fields closely related to his work.

(b) AMBIGUITY. If a single symbol is used for more than one quantity, it must be used so that there cannot be any confusion of the different meanings in the particular context.

(c) IDENTIFICATION. An author should avoid using two symbols whose printed forms are confusingly similar. Examples are ι (iota) and i, zero and capital O.

(d) ECONOMY. Notations should be selected for adaptability to mechanical methods of typesetting. Often the typesetting of a complicated expression can be simplified by introducing a single letter for some complex component of the expression.

3. Secondary Symbols. Subscripts and superscripts should be taken from standard lists if possible; however, it is recognized that special subscripts will be needed frequently. Several subscripts or superscripts, possibly separated by commas, may be attached to a single letter. Standardized abbreviations may appear among subscripts. These devices will aid in avoiding the attachment of subscripts and superscripts to subscripts and superscripts. Brackets should be placed around a symbol with a superscript before an exponent is attached. Reference marks may not be attached to letter symbols.

4. Typography. English letter symbols are printed in italic type. Numerals, subscripts, superscripts, and letters of other alphabets are normally printed in vertical type. Boldface type is preferred when a special alphabet is needed. Type faces with serifs are recommended.

Letter Symbols in Alphabetical Order

English

A	area	L^2
B	formation volume factor	
B_g	gas formation volume factor	
B_o	oil formation volume factor	
B_t	total [two-phase] formation volume factor	
B_w	water formation volume factor	
c	compressibility	Lt^2/m
c_f	formation [rock] compressibility	Lt^2/m
c_g	gas compressibility	Lt^2/m
c_o	oil compressibility	Lt^2/m
c_w	water compressibility	Lt^2/m
C	concentration	*various*
D	depth	L
D	diffusion coefficient	L^2/t
e	influx [encroachment] rate	L^3/t
e_g	gas influx [encroachment] rate	L^3/t
e_o	oil influx [encroachment] rate	L^3/t
e_w	water influx [encroachment] rate	L^3/t
f	porosity	
g	acceleration of gravity	L/t^2
G	total initial gas in place in reservoir	L^3
G_e	cumulative gas influx [encroachment]	L^3
G_i	cumulative gas injected	L^3
G_p	cumulative gas produced	L^3
$\triangle G_e$	gas influx [encroachment] during an interval	L^3
$\triangle G_i$	gas injected during an interval	L^3
$\triangle G_p$	gas produced during an interval	L^3
h	net pay thickness	L
H	gross pay thickness	L
i_g	gas injection rate	L^3/t
i_w	water injection rate	L^3/t
I	injectivity index	L^4t/m
I_s	specific injectivity index	L^2t/m
J	productivity index	L^4t/m
J_s	specific productivity index	L^2t/m
k	absolute permeability	L^2
k_g	effective permeability to gas	L^2
k_o	effective permeability to oil	L^2
k_{rg}	relative permeability to gas	
k_{ro}	relative permeability to oil	
k_{rw}	relative permeability to water	
k_w	effective permeability to water	L^2
K	equilibrium ratio $[y/x]$	
ln	natural logarithm, base e	
log	common logarithm, base 10	
L	moles of liquid phase	
L	length	L
m	mass	m
m	ratio initial reservoir free gas volume to initial reservoir oil volume	
M	molecular weight	
n	total moles	
N	initial oil in place in reservoir	L^3
N_e	cumulative oil influx [encroachment]	L^3
N_p	cumulative oil produced	L^3
$\triangle N_e$	oil influx [encroachment] during an interval	L^3
$\triangle N_p$	oil produced during an interval	L^3
p	pressure	m/Lt^2
p_a	atmospheric pressure	m/Lt^2
p_b	bubble-point [saturation] pressure	m/Lt^2
p_c	critical pressure	m/Lt^2
p_{cf}	casing pressure, flowing	m/Lt^2
p_{cs}	casing pressure, static	m/Lt^2
p_d	dew-point pressure	m/Lt^2
p_e	pressure at external boundary	m/Lt^2
p_f	pressure at the front or interface	m/Lt^2
p_i	initial pressure	m/Lt^2
p_r	reduced pressure	

p_{sc}	pressure at standard conditions	m/Lt^2
p_{sp}	separator pressure	m/Lt^2
p_{tf}	tubing pressure, flowing	m/Lt^2
p_{ts}	tubing pressure, static	m/Lt^2
p_w	bottom-hole pressure, general	m/Lt^2
p_{wf}	bottom-hole pressure, flowing	m/Lt^2
p_{ws}	bottom-hole pressure, static	m/Lt^2
$\bar{p}$	average pressure	m/Lt^2
$\underline{p}$	dimensionless pressure	
P_c	capillary pressure	m/Lt^2
q	production rate	L^3/t
q_g	gas production rate	L^3/t
q_o	oil production rate	L^3/t
q_w	water production rate	L^3/t
$\underline{q}$	dimensionless production rate	
r	radial distance	L
r_e	external boundary radius	L
r_w	well radius	L
$\underline{r}$	dimensionless radial distance	
R	universal gas constant [per mole]	mL^2/t^2T
R	producing gas-oil ratio	
R_p	cumulative gas-oil ratio	
R_s	solution gas-oil ratio [gas solubility in oil]	
R_{sw}	gas solubility in water	
S	saturation	
S_g	gas saturation	
S_{gc}	critical gas saturation	
S_{gr}	residual gas saturation	
S_o	oil saturation	
S_{or}	residual oil saturation	
S_w	water saturation	
S_{wc}	critical water saturation	
S_{wr}	residual water saturation	
t	time	t
$\underline{t}$	dimensionless time	
T	temperature	T
T_c	critical temperature	T
T_r	reduced temperature	
u	volumetric velocity [flow rate per unit area]	L/t
v	velocity	L/t
v	specific volume	L^3/m
V	moles of vapor phase	
V	volume	L^3
V_b	bulk volume	L^3
V_p	pore volume	L^3
V_s	solid volume	L^3
V_M	volume per mole	L^3
W	initial water in place in reservoir	L^3
W_e	cumulative water influx [encroachment]	L^3
W_i	cumulative water injected	L^3
W_p	cumulative water produced	L^3
$\triangle W_e$	water influx [encroachment] during an interval	L^3
$\triangle W_i$	water injected during an interval	L^3
$\triangle W_p$	water produced during an interval	L^3
x	mole fraction of a component in liquid phase	
y	mole fraction of a component in vapor phase	
z	mole fraction of a component in mixture	
z	gas deviation factor [compressibility factor, $z = pV/nRT$]	

Greek

α	alpha	mobility ratio' $[\lambda_1/\lambda_2]$	
β	beta	thermal expansion coefficient	$1/T$
$\triangle$	delta	difference $[\triangle x = x_2 - x_1$ or $x_1 - x_2]$	$[x]$
η	eta	hydraulic diffusivity $[k/fc\mu$ *or* $\lambda/fc]$	L^2/t
λ	lambda	mobility $[k/\mu]$	L^3t/m
λ_g	lambda	gas mobility	L^3t/m
λ_o	lambda	oil mobility	L^3t/m
λ_w	lambda	water mobility	L^3t/m
μ	mu	viscosity	m/Lt
μ_g	mu	gas viscosity	m/Lt
μ_o	mu	oil viscosity	m/Lt
μ_w	mu	water viscosity	m/Lt
ν	nu	kinematic viscosity	L^2/t
ρ	rho	resistivity[2] [electrical]	$[ohms]L$
ρ	rho	density	m/L^3
ρ_g	rho	gas density	m/L^3
ρ_o	rho	oil density	m/L^3
ρ_w	rho	water density	m/L^3
σ	sigma	surface tension [interfacial tension]	m/t^2
τ	tau	tortuosity	
Φ	phi [capital]	potential	*various*
Ψ	psi [capital]	stream function	*various*

Subscripts in Alphabetical Order

a	atmospheric
b	bubble-point or saturation [except when used with volume]
b	bulk [used with volume only]
c	capillary [used in P_c only]
c	critical
cf	casing, flowing [used with pressure only]
cs	casing, static [used with pressure only]
d	dew-point
d	differential separation
e	cumulative influx or encroachment
e	external boundary conditions
f	flash separation
f	front or interface
f	formation or rock
g	gas
i	initial value or conditions
i	cumulative injected
L	liquid
M	molal [used with volume only]
max	maximum
min	minimum
o	oil
p	cumulative produced
p	pore [used with volume only]
r	reduced
r	relative
r	residual
s	gas-oil solution [used in R_s only]
s	solid [used with volume only]
s	specific [used with *J* and *I*]
sc	standard conditions
sp	separator conditions
sw	gas-water solution [used in R_{sw} only]
t	total
tf	tubing, flowing [used with pressure only]
ts	tubing, static [used with pressure only]
w	water
w	well conditions
wf	bottom-hole, flowing [used with pressure only]
ws	bottom-hole, static [used with pressure only]

Modifying Signs

$\bar{x}$	average or mean value of a quantity x
$\underline{x}$	dimensionless quantity proportional to x

Notes

1. When the mobilities involved are on opposite sides of an interface, the mobility ratio will be defined as the ratio of the displacing phase mobility to the displaced phase mobility, or the ratio of the upstream mobility to the downstream mobility.
2. The letter *R* will be retained for electrical resistivity in the list of electric well-logging symbols which is being prepared by a subcommittee. ★★★

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Botset to Speak on Water Flooding at Urbana, Ill.

Professor Holbrook G. Botset, head of the Department of Petroleum Engineering at the University of Pittsburgh, will give a special series of lectures on water flooding on Feb. 10-11. He will speak in Urbana, Ill., at a Petroleum Engineering Conference sponsored by the Illinois State Geological Survey in cooperation with the oil and gas associations and engineering and geological societies of the Illinois Basin.

Subjects to be covered are: basic physical factors controlling production of fluids from reservoir rock; basic physical factors affecting the success of waterflood operation; and waterflood operations and recent developments in flooding techniques.

AUTHORS

(Continued from Page 36)

RICHARD A. MORSE received his BS in petroleum engineering from the University of Oklahoma in 1942 and his MS from Pennsylvania State. In 1947, he joined Stanolind, where he is currently reservoir engineering research section supervisor.

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JOHN R. MCMILLAN, Petroleum Branch chairman, has been named executive vice-president of Monterey Oil Co. He was president of Fullerton Oil and Gas Corp. when that company was purchased recently by Monterey. He joined Fullerton in 1943 as petroleum engineer and assistant manager of field operations, and later became a director and vice-president in charge of production and exploration, before assuming the presidency. For 14 years prior to accepting the position with Fullerton, he worked with Barnsdall Oil Co. in Los Angeles. This included three years as a draftsman prior to his graduation from California Institute of Technology.

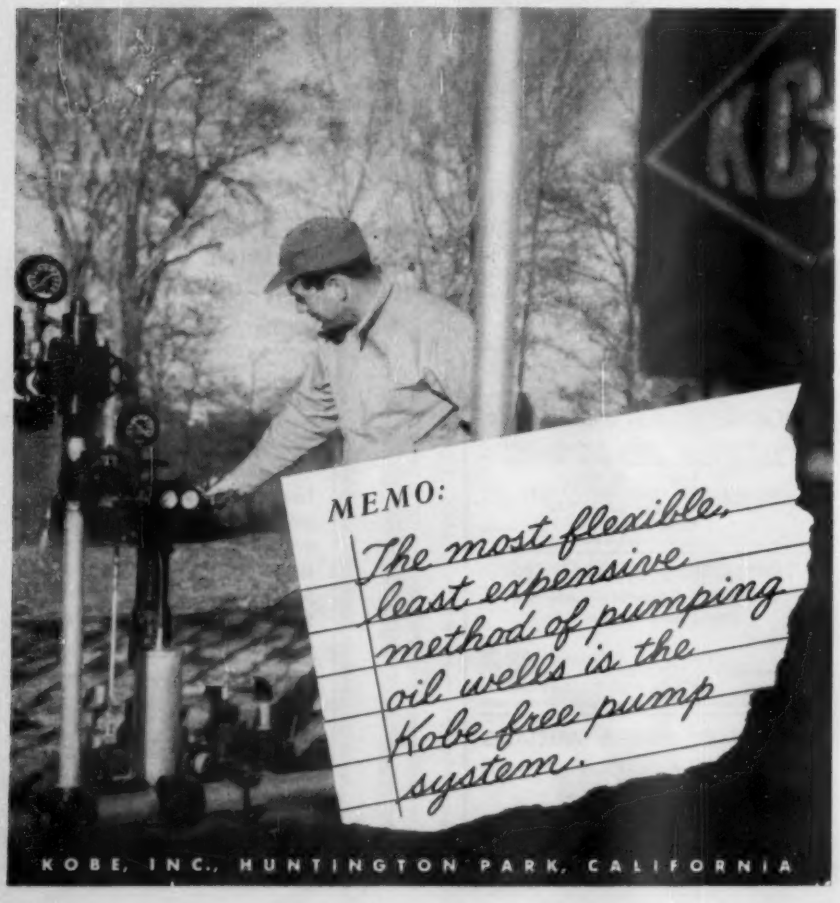
DAVID J. COZAD is now with The Pure Oil Co.'s Gulf Coast Producing Division in Houston. Prior to his recent change he was with the Southwest Research Institute in San Antonio.

WELDON L. PORTER has been appointed a special representative of Welex Jet Services, Inc., and will work from the Dallas Welex sales office. The 1940 University of Texas petroleum engineering graduate has worked with Hunt Oil Co. of Dallas since 1951. Prior to that he had served as a production and drilling engineer throughout Texas, Louisiana, Mississippi, and Illinois. In his new position he will contact oil producers in the Dallas area on Welex special tools and services.

J. K. CRANE, left, and WARREN L. SALLEE have recently received changes of assignments in the Dowell, Inc., organization. Crane, formerly district engineer at Salem, Ill., has been transferred to the company's general office, Tulsa. Sallee has been promoted to district engineer of the New Orleans district. For the past two years he has been sales engineer at the general office in Tulsa.

C. WILLIAM ZUBLIN has accepted the position of sales manager of Petroleum Engineering Associates, Inc., in Pasadena, Calif. He was formerly assistant engineer and field supervisor of Universal Engineering Co., of Los Angeles, where he specialized in drainhole equipment. He received his education at the University of Southern California and Massachusetts Institute of Technology.

WILLIAM L. CRAIG has been named district manager in charge of a new office opened by Evans Production Corp. in Tyler, Texas. The Louisiana State University graduate joined Evans Production on Nov. 1, 1954, after being associated with DeGolyer and MacNaughton for four years. Prior to that he was assistant chief petroleum engineer with Arkansas Louisiana Gas Co.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The Institute desires to extend its privileges to every person to whom it can be of service, but does not desire as members persons who are unqualified. Institute members are urged to review this list as soon as possible and immediately to inform the Secretary's office if names of people are found who are known to be unqualified for AIME membership.

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Merkel — Hanson, Torlif (M); Loflin, Wilburn Monroe (M); Pratt, Posie Ross (A).
Midland — Judson, Edward Harry (C/S-A-M); Rike, James Lee (M).
Odessa — Mardirosian, Azad (J).
Overton — Hubbard, Robert Ellis (J); Lawless, Fred Eugene (J).
Pampa — Sidwell, Eugene Reid (R, C/S-S-J).
Pleasanton — Lee, Richard James (M).
Snyder — Schulz, Edward B. (A).
Sweetwater — Larson, John Herbert (M); Paxton, John William (J).
Wichita Falls — Montfort, Kenneth Lee (J).
Wink — Ilfrey, Allen Haden (M); Wirsching, Joseph Edward (J).
Winters — Bybel, Edward John (A); Cooke, Robert Neill (J); Latimer, James Robert, Jr. (M).

West Virginia
Huntington — Latimer, Warren E. (C/S-A-M).

Australia
Sydney, N. S. W. — Strevens, John Lloyd (R, M).

Bolivia
La Paz — Hinojosa, Eduardo (M).

Indonesia
Pladju, Sumatra — Outmans, Harry Donald (C/S-A-M).

South Iran
Abadan — Graham, William Joseph (C/S-A-M).

Venezuela
Maracaibo — Barberii, Efrain Eneferio (C/S-A-M). ★★★

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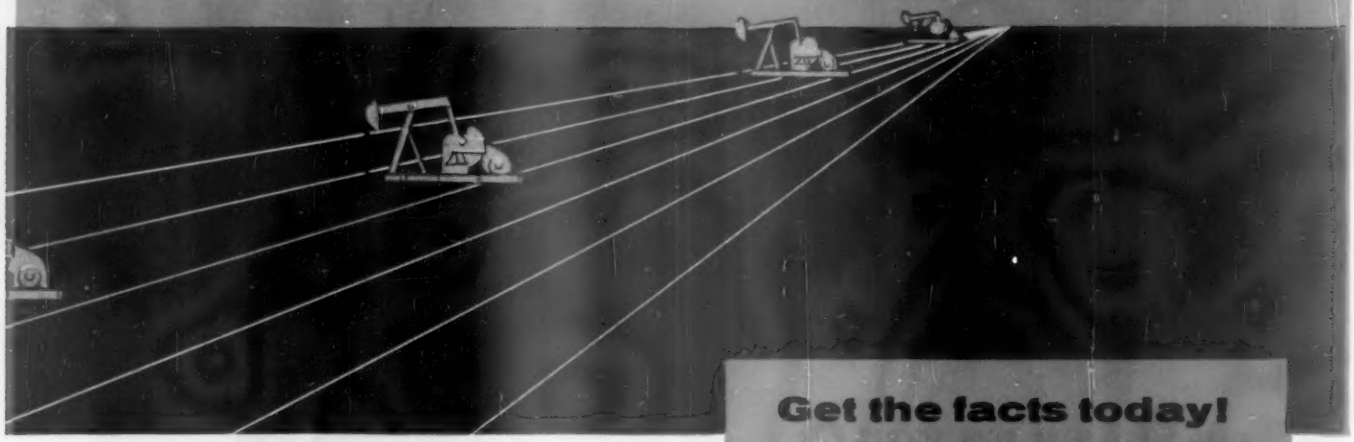

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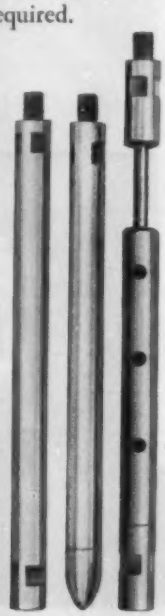

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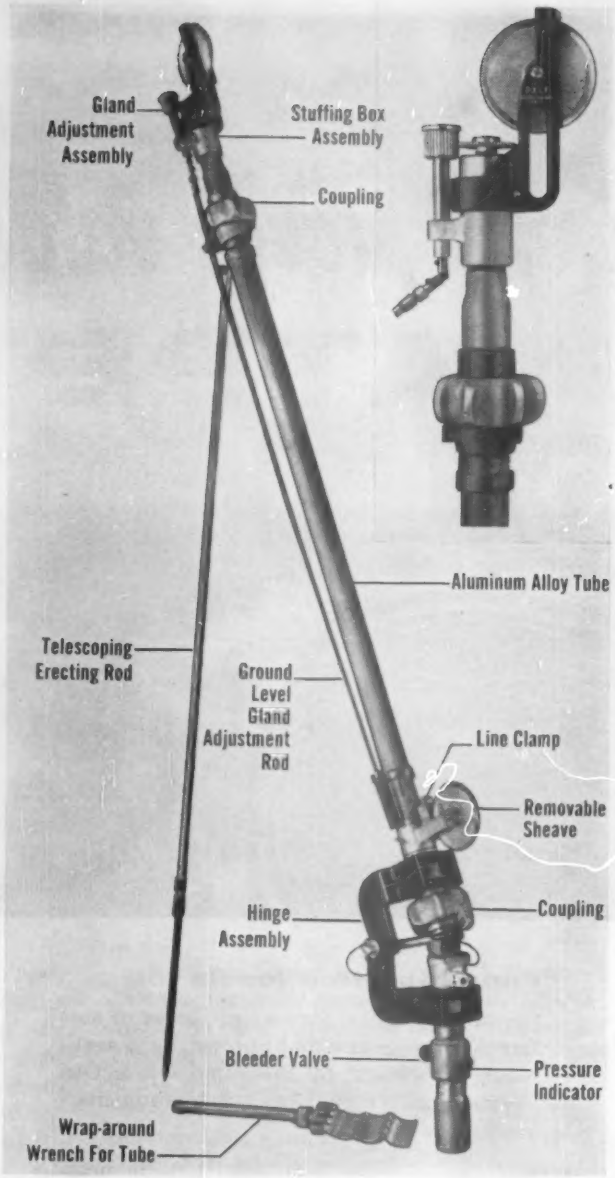

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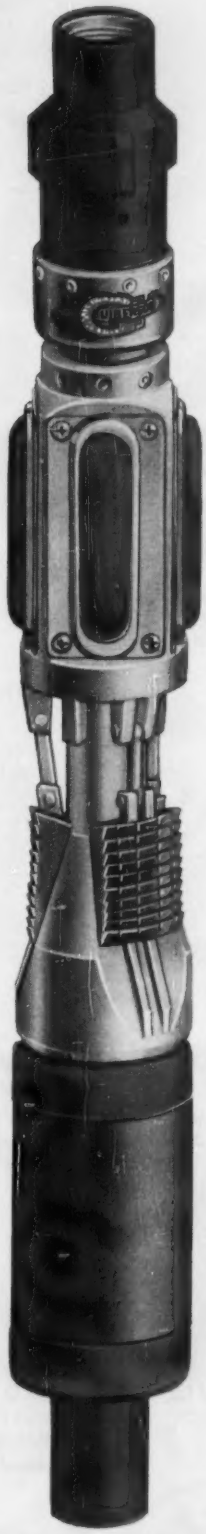

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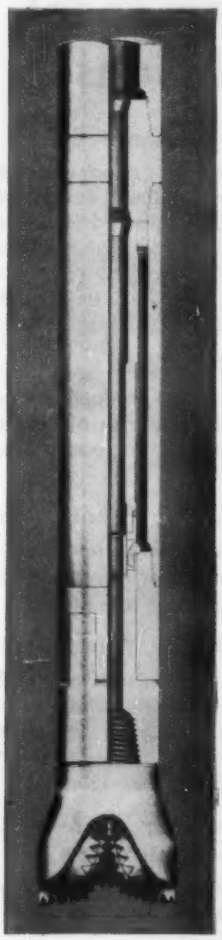

Receiving sub in drilling position — positioned between drill collar and bit. Caliper instrument is dropped or pumped down just prior to pulling out of hole.

Gives you a NEW HIGH in accurate caliper logging — with a NEW LOW in rig time

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Saves rig time because it eliminates time lost in rigging up and running wire line caliper.

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Two-speed recording gives either a detail or a normal chart.

Let us give you all the facts about the new Johnston Hydraulic Hole Caliper and its many uses where extremely accurate measurement and recording of subsurface conditions are required.

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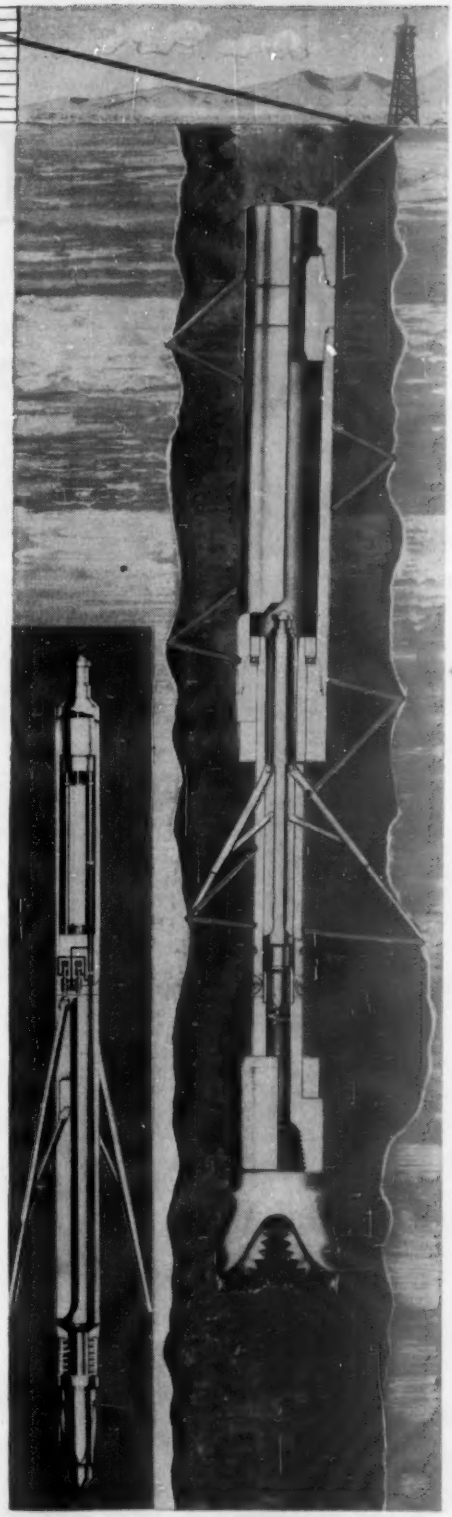

This is the Caliper Instrument with cutaway view of the hydraulic system, clock and chart compartment.

Receiving sub is open and Caliper in measuring position. Caliper instrument unlocks sub as it is indexed in place.

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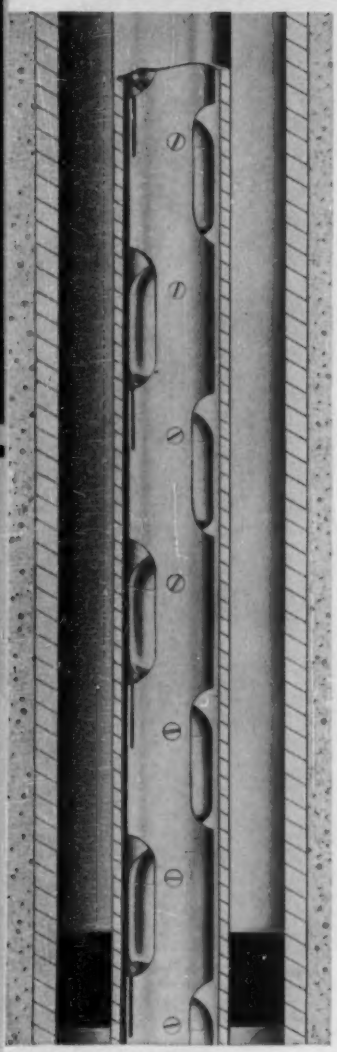

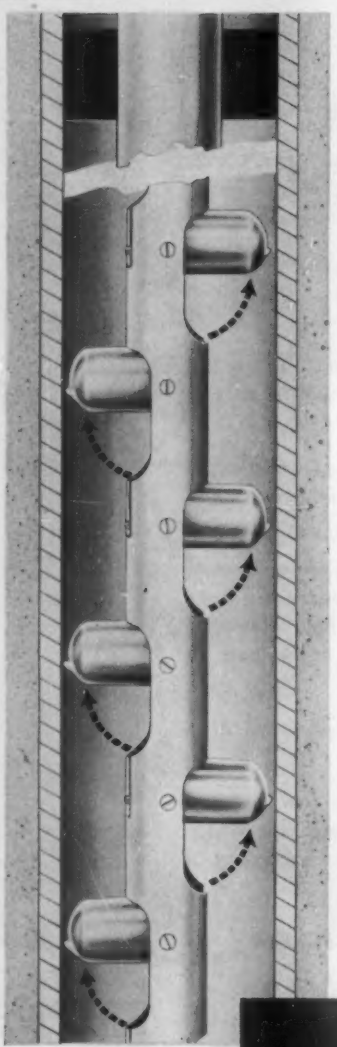

As shown at left, the Swing Jet carrier runs smoothly down 2-inch tubing in closed position.

At right, full-powered jets are snapped into position at firing zone.

How Welex Swing Jets Give Better Permanent-Type Completions

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Swing Jet

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Gulf Coast

In Zapata County, a gas well had been perforated and was making only one-half million cubic feet. One run with the Welex Swing Jet to perforate 12′ at four holes per foot resulted in an immediate increase to one million cubic feet. A test four months later showed the well was producing 4 million cubic feet.

West Texas

A well in Andrews County had been set up for a permanent type completion in order to economize completion costs. The mud in 5½″ casing was displaced with oil, and open-end tubing with a hook-wall packer was run to a point just above the perforating zone. A single run was made with the Welex Swing-Jet to perforate the interval 12,606′ to 12,619′, four holes per foot. Before Welex equipment could be moved from the location, the well was cleaning and flowing to pits without chemical or hydraulic treatment.

Oklahoma

In Grady County, Welex Swing Jet was used to perforate 20′ from 10,225′ to 10,245′ at 8 holes per foot. Following three swabbing runs, the well flowed 94 barrels of oil per hour. A test two months later showed same rate of flow and zone had not been treated in any manner.

Additional data and identification of the wells above can be obtained by writing Welex Jet Services, Inc., Fort Worth.

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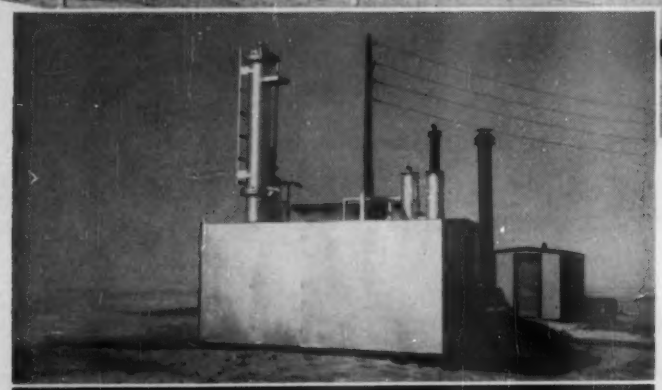
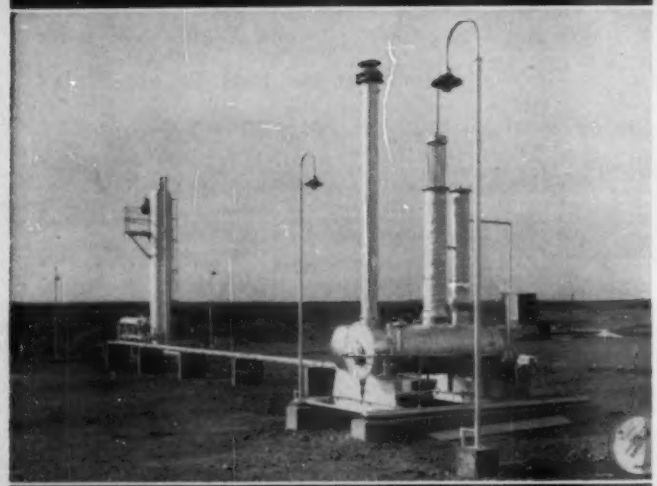
NATIONAL GLYCOL DEHYDRATION AND LOW TEMPERATURE EXTRACTION (LTX®) *Equipment*



National 500 mcf/day, 125 # WP Glycol Dehydrator — N. Dakota



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A 30" x 12½', 1200 psi LTX with Glycol Injection and a 24" x 15', 300 psi Stabilizing Desorber for 10,000 mcf per day operating on lease in South Texas.

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SIMPLIFIED FORM of the MATERIAL BALANCE EQUATION

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INTRODUCTION

The material balance equation has been used for many years by engineers to determine reservoir performance. The use of this equation in general has been twofold: first, to determine the oil-in-place in a reservoir; and second, to predict the future performance. The Schilthius form of the material balance equation, or one equivalent to it, has been used by many of the engineers. The use of the Schilthius form in predicting future performance has proved to be laborious in that one generally must make several estimates at each step of the trial and error calculation before arriving at a check of the oil-in-place.

A method is presented for expediting the calculations. The Schilthius form of the material balance has been rearranged into a more useable form. In using the material balance to predict the future performance of a reservoir, it has become common practice to estimate the incremental oil production for each step of the calculation which corresponds to a given pressure reduction. Instead of estimating the incremental oil production, the method outlined in this paper better lends itself to estimating the instantaneous gas-oil ratio. A check of oil-in-place is more easily accomplished by estimating gas-oil ratio since it is less sensitive to small inaccuracies. This method incorporates the same self-checking feature inherent in the Schilthius form.

DEVELOPMENT OF SIMPLIFIED EQUATION

In the development of the simplified equation, the Schilthius form of the material balance equation will be used.

$$N = \frac{n[U + (r_a - S_a)\alpha] - (W - w)}{(U - U_a) + M\dfrac{U_a}{\alpha_a}(\alpha - \alpha_a)} \quad . \quad (1)$$

where $U = \beta + (S_a - S)\alpha$

$U_a = \beta_a$

$r_a = \dfrac{G}{n}$

Substituting in Equation 1 for U, U_a, and r_a and rearranging terms

$$N = \frac{n\left(\frac{\beta}{\alpha} - S\right) + G - \frac{1}{\alpha}(W - w)}{\left(\frac{\beta}{\alpha} - S\right) - \left(\frac{\beta_a}{\alpha} - S_a\right) + M\beta_a\left(\frac{1}{\alpha_a} - \frac{1}{\alpha}\right)} \quad . \quad (2)$$

In Equation 2, the cumulative oil production (n) is multiplied by a factor which is uniquely a function of pressure. Also, the cumulative gas production (G) and net water influx are also multiplied by factors which are a function of pressure alone. These factors are called (ϕ_a), (ϕ_g), and (ϕ_w) and are defined as follows:

$$\phi_a = \frac{\left(\frac{\beta}{\alpha} - S\right)}{\left(\frac{\beta}{\alpha} - S\right) - \left(\frac{\beta_a}{\alpha} - S_a\right) + M\beta_a\left(\frac{1}{\alpha_a} - \frac{1}{\alpha}\right)}$$

$$\phi_g = \frac{1}{\left(\frac{\beta}{\alpha} - S\right) - \left(\frac{\beta_a}{\alpha} - S_a\right) + M\beta_a\left(\frac{1}{\alpha_a} - \frac{1}{\alpha}\right)}$$

$$\phi_w = \frac{\frac{1}{\alpha}}{\left(\frac{\beta}{\alpha} - S\right) - \left(\frac{\beta_a}{\alpha} - S_a\right) + M\beta_a\left(\frac{1}{\alpha_a} - \frac{1}{\alpha}\right)}$$

Using these factors, Equation 2 becomes

$$N = n\phi_a + G\phi_g - (W - w)\phi_w \quad . \quad . \quad . \quad (3)$$

The equation in this form is easier to manipulate mathematically than any of the previous forms which have been used. Sources of data for the pressure factors ϕ_a, ϕ_g, and ϕ_w are a bottom-hole fluid analysis and the ratio of initial gas cap volume to oil volume in the reservoir.

AID IN DETERMINING THE ORIGINAL OIL-IN-PLACE

Each of the curves ϕ_a, ϕ_g, and ϕ_w have a similar shape. Each is infinite at the bubble point pressure. As the pressure is reduced below the bubble point, the

Manuscript received in Petroleum Branch office on July 1, 1954.

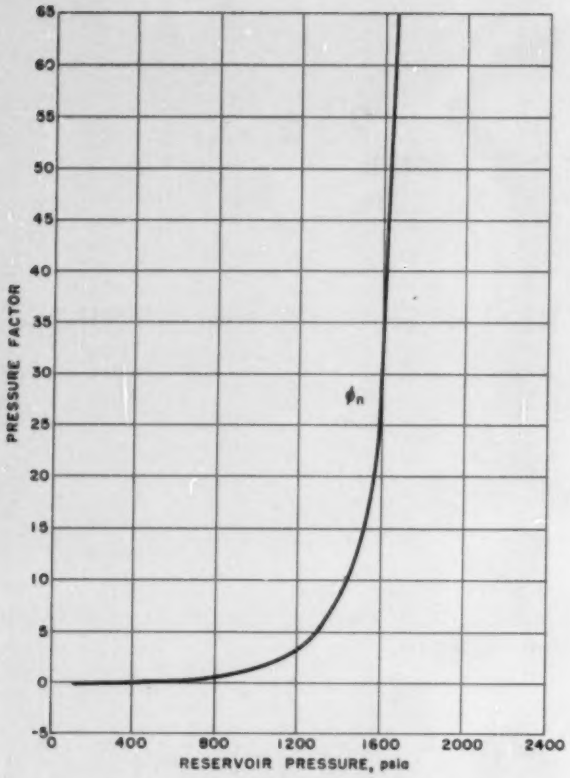

FIG. 1 — OIL PRESSURE FACTOR VS RESERVOIR PRESSURE.

value of the functions reduces rapidly. To illustrate this fact, in the example which will be cited later, the values of ϕ_n, ϕ_g, and ϕ_w are infinite at the bubble point of 1,690 psia. When the pressure is reduced to 1,600 psia, the values of ϕ_n, ϕ_g, and ϕ_w are as follows: ϕ_n = 36.60, ϕ_g = 0.40, and ϕ_w = 58.56.

Because of the rapidly changing nature of these factors near the bubble point pressure and the fact that the average reservoir pressure is seldom known precisely, an accurate determination of oil-in-place when the reservoir pressure is near the bubble point is seldom reliable. This is a characteristic of all estimates of oil-in-place from material balance calculations.

The shapes of ϕ_g and ϕ_w curves are of such nature so as to decrease constantly as pressure decreases. The values of these functions are always positive. The shape of the ϕ_n curve is somewhat more unique. At low pressures, this factor becomes negative. Once ϕ_n becomes negative, it will continue to decrease as pressure decreases. With still greater reduction in pressure, this factor reaches a minimum numerical value after which the value increases. At atmospheric pressure, the value of ϕ_n is a small positive number. Figs. 1 and 2 illustrate the shape of these curves.

As can be seen from Equation 3, the error in oil-in-place that would result from erroneous pressure measurements is a function of the slopes of the pressure factor curves. This fact makes the determination of oil-in-place unreliable in the early life of a reservoir by means of material balance calculations. However, after the reservoir pressure is reduced to the point where the slopes of the pressure factor curves are less steep, the oil-in-place can be determined with reasonable precision.

The following equation will indicate the error in oil-in-place that could be expected from an error of 1 psi in the measurement of static pressure:

$$\text{Error in } N = n(\varepsilon\phi_n) + G(\varepsilon\phi_g) - (W - w)(\varepsilon\phi_w) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

In fields where repeated material balance calculations are necessary, the pressure factors could be plotted as a function of pressure and filed for future use. With such factors having been calculated previously, the calculation of the oil-in-place would be only a few minutes job after having determined the average reservoir pressure and the production data.

AN AID IN THE PREDICTION OF FUTURE PERFORMANCE

Up to this point, we have referred to Equation 3 primarily as a tool for determining oil-in-place. If this were its only use, very little would be gained by using this simplified form. The calculations of future performance can be simplified considerably by using a revised form of Equation 3. To accomplish this revision, consider some of the equalities which are normally used in predicting future performance.

$$n_i = n_{i-1} + \Delta n$$
$$G_i = G_{i-1} + \Delta G$$
$$\Delta G = \left(\frac{r_i + r_{i-1}}{2}\right)\Delta n$$

Substituting these equalities in Equation 3 and assuming no water influx or water production,

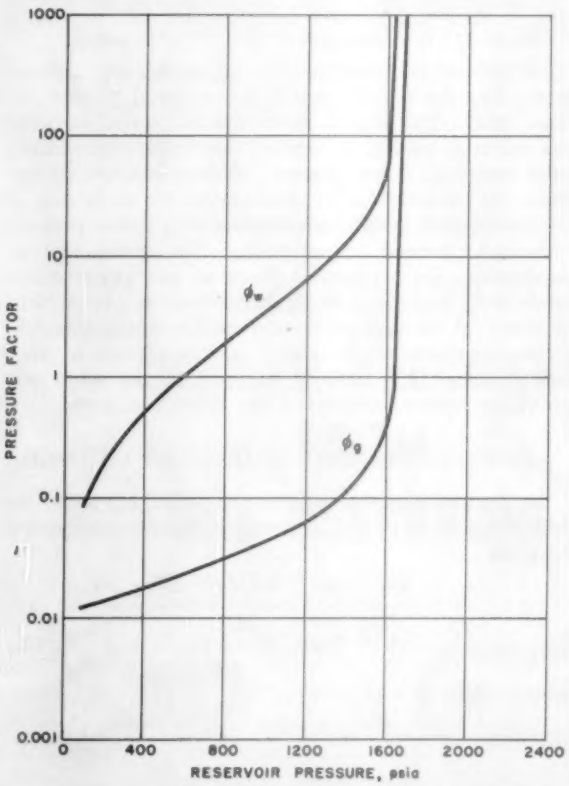

FIG. 2 — GAS AND WATER PRESSURE FACTORS VS RESERVOIR PRESSURE.

CALCULATION SHEET I — PREDICTION OF FUTURE PERFORMANCE FOR DEPLETION DRIVE OPERATIONS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
P	r_i (Estimated)	r_a	ϕ_n	ϕ_g	$n_{i-1}\phi_n$	$G_{i-1}\phi_g$	(6)+(7)	1.0—(8)	$r_a\phi_g$ (3)×(5)	(4)+(10)	Δn (9)/(11)	n_i $(n_{i-1}+\Delta n)$	1.0—n_i	β	(14) × (15)	s_o	s_L
1100												0.0895					
900	450	389	0.818	0.0352	0.0732	0.565	0.6382	0.3618	14.01	14.83	0.0244	0.1139	0.8861	1.168	1.035	.720	.840
700	550	499	0.284	0.0256	0.0322	0.658	0.6902	0.3098	12.77	13.05	0.0238	0.1377	0.8623	1.143	0.986	.686	.806
500	650	608	0.0142	0.0202	0.0020	0.763	0.7650	0.2350	12.28	12.29	0.0191	0.1568	0.8432	1.118	0.943	.656	.776

SOLUTION OF PREDICTION EQUATION

SOLUTION OF LIQUID SATURATION EQUATION

(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)
K_g/K_o (From Curve)	$F=\frac{\mu_o\beta}{\mu_g\alpha}$	$F\frac{K_g}{K_o}$ (19) × (20)	S	r_i (21)+(22)	$\left(\frac{r_i+r_{i-1}}{2}\right)$	ΔG (12)x(24)	$\frac{G_i}{G_{i-1}+\Delta G}$	$G_i\phi_g$ (26)x(5)	$n_i\phi_n$ (13)x(4)	N (27)+(28)
				345.0			16.052			
0.046	8410	386.7	60.8	447.5	396.2	9.667	25.719	9.905	0.093	0.998
0.072	7160	515.2	50.5	565.7	506.6	12.057	37.776	0.967	0.039	1.006
0.105	6030	633.4	40.2	673.4	619.5	11.832	49.608	1.002	0.002	1.004

SOLUTION OF GAS-OIL RATIO EQUATION

Column No.	Explanation
(1)	Reservoir Pressure
(2)	Estimated Instantaneous Gas-Oil Ratio (see Column 23)
(3)	Average Gas-Oil Ratio
(4)	Oil Pressure Factor
(5)	Gas Pressure Factor
(12)	Incremental Oil Production
(13)	Cumulative Oil Production
(15)	Reservoir Volume Factor
(17)	Oil Saturation

SOLUTION OF MATERIAL BALANCE EQUATION

Column No.	Explanation
(18)	Liquid Saturation
(19)	Relative Permeability of Gas to Oil
(20)	Conversion Factor
(21)	Free Gas-Oil Ratio
(22)	Solution Gas-Oil Ratio
(23)	Calculated Instantaneous Gas-Oil Ratio (see Column 2)
(24)	Average Gas-Oil Ratio
(25)	Incremental Gas Production
(29)	Original Oil-in-Place For Checking Consistency of Calculations

$$N = n_{i-1}\phi_n + G_{i-1}\phi_g + \left[\phi_n + \left(\frac{r_i + r_{i-1}}{2}\right)\phi_g\right]\Delta n$$

It has become common practice to use the original oil-in-place (N) as 1 bbl of stock tank oil. This practice simplifies the calculations. Substituting $N = 1$ in the above expression and solving for Δn, the following equation is determined:

$$\Delta n = \frac{1 - (n_{i-1}\phi_n + G_{i-1}\phi_g)}{\phi_n + \left(\frac{r_i + r_{i-1}}{2}\right)\phi_g} \quad . \quad . \quad . \quad . \quad (5)$$

It can be seen that only two unknown quantities are in Equation 5. These quantities are the incremental oil production (Δn) and the instantaneous gas-oil ratio (r_i). All of the other factors are either known from the previous step of the calculations, production data, or are functions of pressure.

In the past it has been the practice of estimating the incremental oil production Δn and solving for a compatible value of the gas-oil ratio. A check of the estimate of Δn is made by calculating the original oil-in-place. By estimating the instantaneous gas-oil ratio (r_i), a final check of $N = 1$ will be accelerated as compared to estimating Δn. This is true because the gas-oil ratio is a factor which is much less sensitive to small variations. In fact, a variation of 10 per cent in estimating r_i will result in a difference of approximately 5 per cent in the calculated value of Δn. However, if Δn is estimated and a variation of 10 per cent is made, the calculated gas-oil ratio will be different, approximately 20 per cent, and throw the calculations four times as far out of balance.

As a further aid in the problem of calculating future performance, the engineer should maintain a current plot of the instantaneous gas-oil ratio and average reservoir pressure versus cumulative oil production. Once the trend in these variables is established, an extrapolation of these curves will aid in the estimation of the instantaneous gas-oil ratio for the next step.

It has been found that a check of the oil-in-place is the most difficult early in the problem. After two or three steps, the number of attempts which are necessary to effect a check of the oil-in-place is usually reduced to one or two. It should be pointed out that if the calculation is started at the bubble point pressure, the terms n_{i-1} and G_{i-1} are both equal to zero for the first step below the bubble point.

SAMPLE CALCULATION

The production history for an originally saturated reservoir is as follows:

Pressure, psia	Cumulative Oil Thousand STB	Cumulative Gas Millions bbls at 14.7 psia and 60°F
1690	0	0
1600	398	38.6
1500	1570	155.8
1100	4470	803.0

The calculated pressure factors from bottom-hole sample data are as follows:

P	ϕ_n	ϕ_g
1600	36.60	0.400
1500	14.30	0.179
1100	2.10	0.0508

CALCULATION OF OIL-IN-PLACE

P psia	n Bbls	G Bbls	$n\phi_n$	$G\phi_g$	N STB
1600	0.398 × 10^6	38.6 × 10^6	14.32 × 10^6	15.42 × 10^6	29.74 × 10^6
1500	1.57 × 10^6	155.8 × 10^6	22.45 × 10^6	27.85 × 10^6	50.3 × 10^6
1100	4.47 × 10^6	803.0 × 10^6	9.39 × 10^6	40.79 × 10^6	50.18 × 10^6

It can be seen that the original oil-in-place in this reservoir is approximately 50 million bbls. The calculation at 1,600 psia is a good example of the sensitivity of such a calculation near the bubble point pressure. Since the last two calculations agree so well, the first calculation is probably wrong. If the pressure were 1,620 psia rather than 1,600 psia, as is indicated, the oil-in-place would have calculated to be 50.4 million bbls. Since it is doubtful that reservoir pressure is known within 20 psi, the original oil-in-place must be approximately 50 million bbls.

Calculation of Future Performance

The calculation of the future performance of a reservoir involves the solution of three simultaneous equations which are as follows:

A. Material Balance Equation: $1 = n_i\phi_n + G_i\phi_g$

B. Liquid Saturation Equation: $\sigma_{L_i} = \sigma_w + (1 - \sigma_w)\left(\frac{1 - n_i}{\beta_o}\right)\beta$

C. Gas-Oil Ratio Equation: $r_i = F\left(\frac{K_g}{K_o}\right) + S$

The method of calculation outlined in this paper uses one additional equation:

D. Prediction Equation: $n = \frac{1 - (n_{i-1}\phi_n + G_{i-1}\phi_g)}{\phi_n + \left(\frac{r_{i-1} + r_i}{2}\right)\phi_g}$

The procedure to be followed in solving the above equations is shown on Calculation Sheet 1.

Also included is a portion of the future performance for the same reservoir cited above, starting with the conditions at 1,100 psia and progressing to 500 psia.

NOMENCLATURE

N = Original oil-in-place, STB
n = Cumulative oil production, STB
G = Cumulative gas production, barrels at 14.7 psia and 60° F
U = Volume of 1 STB of oil and its originally dissolved gas at reservoir conditions, dimensionless ratio
U_o = Volume of 1 STB of oil and its originally dissolved gas at bubble point pressure, dimensionless ratio
r_n = Cumulative net produced gas-oil ratio, dimensionless ratio
S = Solution gas-oil ratio, dimensionless ratio
S_o = Solution gas-oil ratio at bubble point pressure, dimensionless ratio
α = Volume of 1 standard cu ft of gas at reservoir conditions, dimensionless ratio
α_o = Volume of 1 standard cu ft of gas at reservoir bubble point conditions, dimensionless ratio
β = Volume of 1 STB of oil at reservoir pressure, dimensionless ratio
β_o = Volume of 1 STB of oil at bubble point pressure, dimensionless ratio
K_g/K_o = Relative permeability of gas to oil
μ_o/μ_g = Relative viscosity of oil to gas
W = Cumulative water influx, barrels
w = Cumulative water production, barrels
$F = \frac{\mu_o}{\mu_g}\frac{\beta}{\alpha}$
M = Ratio of original gas cap volume to original oil volume
σw = Connate water saturation
σL = Liquid saturation
Δn = Incremental oil production between two values of reservoir pressure, STB
ΔG = Incremental gas production between two values of reservoir pressure, barrels at 14.7 psia and 60° F
r_i = Instantaneous produced gas-oil ratio, dimensionless ratio
r_n = Average produced gas-oil ratio between two values of reservoir pressure, dimensionless ratio
$(\varepsilon\phi_n)$; $(\varepsilon\phi_g)$; $(\varepsilon\phi_w)$ = Slopes of Pressure Factor Curves

Subscript $_i$ refers to conditions at pressure being investigated.

Subscript $_{i-1}$ refers to conditions at immediate previous pressure step in calculation; hence, the conditions at each step are always known either from having just been calculated or from measured data.

All values of gas-oil ratio and production data are measured at surface conditions.

ACKNOWLEDGMENT

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AIME

PETROLEUM TRANSACTIONS

RADIOACTIVE TRACERS in OIL PRODUCTION PROBLEMS

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T. P. 3982

ABSTRACT

The development process for the use of radioactive tracers as a means of locating zones of permeability is discussed. The general techniques for the safe handling of radioactive materials is given as developed by the Lane-Wells Co. and Well Surveys, Inc. The problems and successes with tracers in waterflood systems, oil and gas injection profiles, fracture sand tracing, squeeze cement tracing, lost circulation, and cement top location are discussed and illustrated.

INTRODUCTION

The exact location of the permeable zones lying within the productive horizon has been a major problem faced by the petroleum engineer for decades, and it has been a problem which has seldom been solved with certainty. Reservoir engineers usually have to incorporate a question mark in their estimates of future reservoir performance because of blanks in the core data. Although the use of radioactivity or electrical logs for the estimation of porosity has been of great assistance in furnishing a record for the reservoir engineer, this application of logging data has not completely solved the problem. In short, the industry needs an in-situ well surveying method which can locate and estimate the permeability of the zones existing within a given pay section.

The initial development work with radioactive tracers has been towards filling the need for permeability information. Progress to date permits the location of permeable zones with a qualitative estimate of their relative importance with respect to permeability. The ent development work on tracer preparations, borehole effect correction factors, and instrument limitations give a promise of quantitative "permeability profiles" in the near future.

The development work on the radioactive tracer method discussed here began several years ago in the laboratories of Well Surveys, Inc., in Tulsa. At the outset of this work, three approaches to the problem were visualized as follows:

1. A fluid carrying a soluble, chemically inert, gamma ray emitting isotope is pumped down the borehole and out into the permeable zones of the formation. The greater gamma activity of the permeable zones thus permits them to be differentiated from the impermeable zones which contain no active tracer.

It was found difficult to obtain a tracer material which was chemically inert. Absorption to some degree was noted in all experiments. Also, it proved impossible to hold the tracer near the borehole where it could be logged.

2. A fluid carrying a soluble, gamma ray emitting isotope is pumped down the borehole into the permeable formations. In contrast with proposal 1, above, the tracer is chemically active with the fluids and materials in the pore spaces of the permeable zones. The permeable zones are thus indicated by their higher radioactivity level.

The main difficulty in this proposal was finding a tracer material which would not be absorbed by shale as well as in the permeable porosity. Very little field work was done with this system.

3. Radioactive particles suspended within the injection fluid are pumped down the well. As the fluid enters the permeable formations, the radioactive particles are filtered out on borehole wall. The permeable zones are differentiated from the impermeable by the gamma ray activity deposited on the formation wall.

Discussion of this and all following technical papers is invited. Discussion in writing (3 copies) may be sent to the offices of the Journal of Petroleum Technology. Any discussion offered after Dec. 31, 1955, should be in the form of a new paper.
Manuscript received in Petroleum Branch office on Sept. 20, 1954. Paper presented at Petroleum Branch Fall Meeting in San Antonio, Oct. 17-20, 1954 and Pacific Petroleum Chapter Fall Meeting in Los Angeles, Oct. 7-8, 1954.
[1]References given at end of paper.

Successful results were obtained from the very first experiment. Whereas in proposals 1 and 2 the chemical nature of the tracer material was critical, in 3 this problem was solved by preparing an inactive compound and then depending on the physical nature of the tracer for its success. In this respect, though, there are several practical limitations controlling the field application of proposal 3.

1. The borehole must be free of mud and the mudcake must be removed from the well face.

2. The flow rate down the well must be higher than the settling rate of the largest particles.

3. The particle size must be fairly large. Small particles tend to flow into the formation rather than filter out on the well face. In general, particles which pass through a 200 mesh are quite often found to be too small. There appears to be no drastic limitation on the maximum particle size which can be used provided the density of the particles, and the viscosity of the fluid used is such that the settling rate attained is much slower than the flow rate down the well.

4. The radioactive material must remain with the carrier particle after filtering out on the well face. The tracer preparation should allow this no matter how the injection fluid has been treated.

To date, this method has been found useful in the following applications: (1) the determination of permeability profiles on water injection wells; (2) the evaluation of perforating jobs; (3) the evaluation of formation fracturing treatments; and (4) the location of leaks through casing and of thief zones behind pipe which are taking fluid through casing leaks.

Many other problems encountered in petroleum production are also amenable to the use of radioactive tracers as a source of information leading to successful remedial measures. These involve investigations regarding corrosion problems, gravel pack migration or plugging, fracture sand locations, fluid interface markers, and possibly many others. There are 24 different radioisotopes suitable for oil well tracer logging, by reason of their gamma radiation and ready availability. The seemingly infinite variety of chemical and physical preparations using these radioisotopes should allow their use in many applications not yet considered.

OIL FIELD TRACER SAFETY

Tracers for oil field use range from 1 to 2 millicuries for waterflood injection profiles to 100 millicuries or more for interwell tracers. Injection profile units or sand tracer units yield a radiation intensity of 40 to 200 milliroentgens per hour adjacent to the container. They may be handled safely with gloved hands alone providing a time limitation is observed. The time necessary for handling the tracer unit is of the order of a few minutes at the most so that radiation exposures are well below the 50 milliroentgen per day limit.

These very low radiation exposures in the field have been maintained by laboratory preparation and canning of the tracer units for shipment to the field and the field use of injection equipment designed for these canned tracer units. The ingestion hazard is also eliminated by the use of this special injection apparatus and the handling technique established for these operations.

The canned tracer units are opened in the field and the tracer immediately injected into the well by such means as a truck mounted mixing tank and pump unit, a manifold arrangement attached to the regular injection line, or a dump bailer which allows placement of the tracer just above the zone of interest.

The mixing tank and pump unit may be used under most conditions, but is most useful when no well site pump facility is available. With the mixing tank about two-thirds full the tracer unit is emptied into the tank in less than one minute handling time. Consequently, the radiation dosage received is negligible. After adding the tracer, the tank cover is replaced and all further operations are performed at the engine and valve controls.

The manifold tracer injector is used in conjunction with pump systems already at the well. The tracer can, unopened, is inserted into a chamber where two piercing elements open the can to the injection flow line. The main valve is closed, and two bypass valves through the chamber are opened to allow the injection fluid to wash through the can and carry the tracer into the well. After injection of the tracer the main valve may be opened and the bypass valves closed to allow the continuing injection of fluid without restriction of flow.

A dump bailer, utilized for down hole placement of the tracer, is a standard cement dump bailer. The tracer unit is washed out of the can through a funnel into the dump bailer as it hangs suspended over the well. The bailer is then lowered to the desired depth where the tracer is injected. The tracer handling is completed in less than one minute.

Safety equipment used in tracer operations is carried to the job in kit form. This safety kit contains the following items in a compartmented aluminum carrying case:

1. Dosimeters and charger for personnel exposure measurements on a daily basis.
2. Film Badges for personnel exposure measurements on a weekly basis. These film badges also serve as permanent exposure records.
3. Low level survey meter for radioactive contamination location.
4. High level survey for monitoring operations involving larger radiation intensities.
5. Gloves, respirator, and goggles for personnel protection.

Other tools and safety items are generally used in tracer jobs in the field. These include such items as: a shovel, water supply, containers for radioactive waste, and material suitable for decontamination procedures.

RADIOACTIVE TRACERS IN OIL PRODUCTION

Injectivity Profiles

WATERFLOOD INJECTION PROFILE

The successful application of radioactive tracers for injection and permeability profiles in waterflood operations has been amply demonstrated[14,15]. The problems of carrier particle size and tracer fixing on the particle occasionally requires multiple logs for reliable injectivity information.

Fig. 1A is an example of the effect obtained when the tracer material enters the formation and exceeds the detection range of the instrument. The tracer was located by making multiple runs as it entered the open hole. The tracer material used was ½ lb of 50 to 100

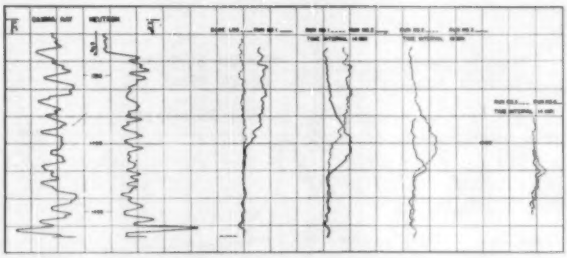

FIG. 1A — TRACER PARTICLE LOSS.

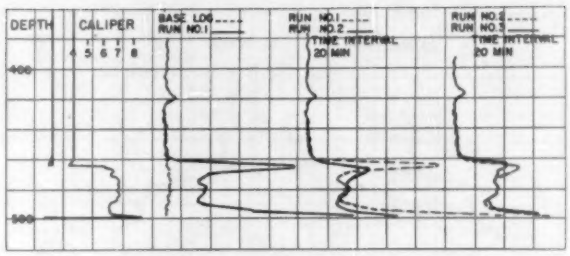

FIG. 1B — TRACER WASHING EFFECT.

mesh resin activated with 1 millicurie of Iodine 131. On the left is a combination gamma ray and neutron log indicating the lithology as a series of sand and shale members. To the right is the base gamma ray log run prior to injection. Run No. 1 shows the tracer slug entering the open hole. Run No. 2, 14 minutes later, shows a smaller slug with the leading edge at 1,420 ft and the trailing edge at 1,360 ft. Run No. 3 shows the slug considerably reduced and indicates that the tracer material is entering the formation. Run Nos. 4, 5 and 6 (4 and 5 not shown) verify this fact for none of the material has appeared below 1,426 ft.

The other problem, more commonly encountered in water floods with a high salt content, is shown by Fig. 1B. With continued injection the isotope is washed off the particle and carried back into the formation with the injected water. Note that the tracer does build up somewhat in contrast to the previous case of the particles being carried back into the formation. This effect may be recognized by the relatively slow decrease in log amplitude as compared with the case where the carrier particles are being lost to the formation.

Various "fixing processes" for resin carrier particles are now being investigated. Partial success has been attained by forming an insoluble precipitate of the radioactive element within the resin. This results in the tracer going into solution at a much slower rate. The desired tracer preparation, though, is one which will hold the radioisotope permanently in the resin. The tracer can then be injected at any convenient time and logged in one run over the injection interval to give the complete picture of the injectivity profile. This particular problem is avoided in waterflood studies by the use of a radioisotope carried by powdered charcoal.

OIL INJECTION PROFILE

Oil injection profiles are being utilized to study many problems and well conditions. One such study makes use of an injection profile with radioactive oil tracers before and after fracture treatments to ascertain which zones were fractured and measure the effective permeability changes.

The procedure followed in obtaining the results represented in Fig. 2 was to inject with the oil a 1 millicurie unit of Iodine 131 activated resin. An injection profile was run in 4¾-in open hole through 2-in tubing with a packer set in 5½-in casing. The tracer logs were obtained with a 1¾-in diameter counter type instrument.

Fig. 2 shows the combination gamma ray and neutron log run previous to treatment and the two tracer surveys. The apparent high porosity on the neutron between the casing seat and 5,430 ft is due to a change from 7⅞-in open hole to 4¾-in. This is a neutron effect resulting from the change in the fluid volume between the instrument and the formation. The before-frac tracer survey shows the injection fluid entering two zones 5,422 to 5,430 ft and 5,436 ft to total depth. The log amplitude above 5,420 ft indicates some tracer still entering the open hole. The final equilibrium log was not obtained on this survey. The logging instrument was removed from the hole, and the well was then fractured and flushed. The after-frac tracer survey, performed in the same manner as the first, indicates an increased permeability for the zone from 5,436 to 5,440 ft. The upper zone from 5,422 to 5,430 ft shows an injectivity comparable to the before-frac indication.

GAS INJECTION PROFILE

Many repressuring projects are in operation using gas. To the authors' knowledge it has been only recently that successful gas injection profiles have been obtained on such projects. In one field in West Texas, the production is from two zones, A and B. Zone B contains gas in gaseous phase while the Zone A gas is definitely in the liquid phase. In an earlier effort to determine the zones taking gas, one well was used to run a fluid type injection profile using oil for injection and an oil wet tracer preparation for the survey. The results of this oil injection profile, while valid as an indication of permeability to oil, were not ideal for indicating gas permeability.

At a later date, a project was initiated to obtain injection profiles on four wells using gas. Well conditions consisted of 160 ft of 4¾-in open hole, 5½-in casing, a Baker production packer and 2-in tubing. In the well to be described, 170,000 cu ft of gas per day at 550 psi was being injected. The wellhead was removed and a high pressure packing gland and lubricator were installed to allow the 1⅜-in diameter gamma ray instrument to be put through the tubing and log the open hole while injecting the gas. The tracer used was a laboratory synthesis of an oil soluble gas using Iodine 131 as the radioactive material. The tracer was brought to the well contained under pressure in a glass ampoule. Injection was accomplished by breaking the ampoule in a small cylinder and washing it into the main gas injection line with a high pressure of inert gas connected to the small cylinder.

The tracer, being soluble in oil, is partially absorbed by the oil wet formation near the borehole wall. A sufficient proportion of the radioactive material thus remains near the borehole wall where the gas is entering the formation to provide a good gas injectivity profile.

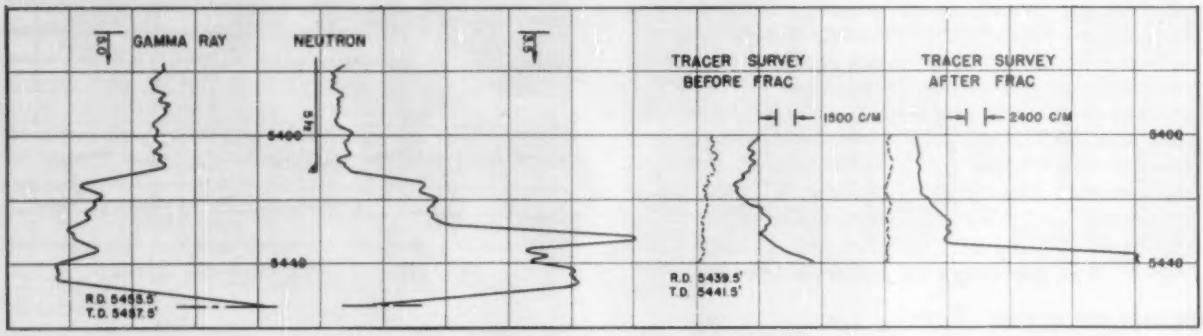

FIG. 2 — BEFORE-AND-AFTER-FRAC TRACER SURVEY.

Fig. 3 is the profile obtained on one of the wells. Presented is the combination log and the base run gamma ray curve. Run No. 1 was obtained as soon as the tracer reached open hole and shows the tracer slug to be approximately 90 ft in length. Run No. 2, 20 minutes later, shows the slug to have narrowed to 40 ft and indicates the greater portion of the gas entering Zone B from 4,680 to 4,730 ft. A third run, obtained 50 minutes after Run No. 2, shows very little change. Accordingly, it is felt that the difference in the Base Log and Run No. 2 indicates the zone taking the greater portion of the gas.

WELL TREATMENT TRACERS

Radioactive tracers may be used to a good advantage in many oil well treatment processes. The essential technique is to mix an appropriate tracer preparation with the well treatment material for future or concurrent survey. Sand, treated to be radioactive, mixed with fracture sands (Hydra-frac, Sand-frac, Chem-frac, etc.) can reveal the exact zones of fracture in the well whether they be in permeable or non-permeable formation. A radioactive solution mixed with the cement slurry for selective plugging can be used to locate the zone and extent of the cement travel. A radioactive solution mixed with well treatment acids is an excellent method of controlling and/or locating zones taking acid. Many others might be listed but the following examples are typical:

TRACERS FOR FRACTURE TREATMENTS

Before any tracer processes for fracture treatments had been attempted, it was questioned whether the active sand should be mixed with all of the propping sand or only the last 5 or 10 per cent of the total. While more experience is desirable before positive conclusions can be drawn, the results of two early experiments indicate an advantage for the latter technique.

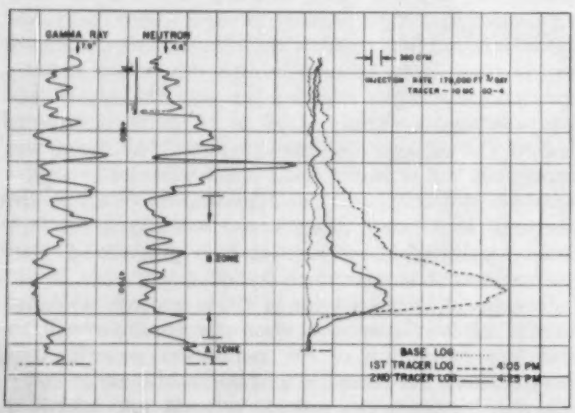

FIG. 3 — GAS INJECTION PROFILE.

Fig. 4A shows the log obtained with the tracer mixed with all of the sand. Note the relatively low amplitude of the tracer log as compared with the base log even though a total of 30 millicuries of Iridium 192 was used in only 3,000 lb of sand. The fluid used on this fracture job included a 15 per cent inhibited acid. The Iridium 192 used to activate the sand was unaffected by this acid indicating a particular utility for the isotope of this chemically inactive metal.

Fig. 4B shows a log obtained with the tracer added to the last 500 lb of sand of a total of 10,000 lb. In this case the tracer consisted of only 10 millicuries of Iridium 192. The resultant log is of such amplitude as to make a base log unnecessary. The base log in this illustration is comparable to the tracer log above 3,085 ft depth. This is a definite advantage both with respect to the tracer and the logging costs.

A further advantage to adding the frac-tracer to only the final part of the frac sand is the reduced radioactivity hazard. Regardless of the quantity of sand used a tracer of 10 millicuries appears to be sufficient for the job.

PLUGGING AGENT TRACERS

Plugging agents can be activated with radioisotopes so as to allow a measurement of the location and extent of the treatment. Fig. 5 illustrates the results obtained in tracing a cement squeeze job. The 35-ft sand zone between 2,965 ft and 2,930 ft was cased and then perforated from 2,948 ft to 2,946 ft with 12 holes. Approximately 5 millicuries of Iodine 131 in solution was mixed with 8 bbl of diesel fuel. This was used to mix 68 sacks of cement to squeeze the well. The well squeezed normally, with a final pressure of 3,000 psi. It is apparent from the tracer log that all of the sand section took cement. This could have been due to a poor original cement job on the casing.

DRILLING AND COMPLETION PROBLEMS

Two of the following illustrations of the use of radioactive tracers in drilling and completion problems were obtained using radioactive casing compound No. 60, a byproduct of radium and uranium refining. This material is suitable for the problems discussed, but because of its physical nature and long half-life of 1,590 years this radioactive casing compound is limited in the extent of its usefulness. The use of radio-

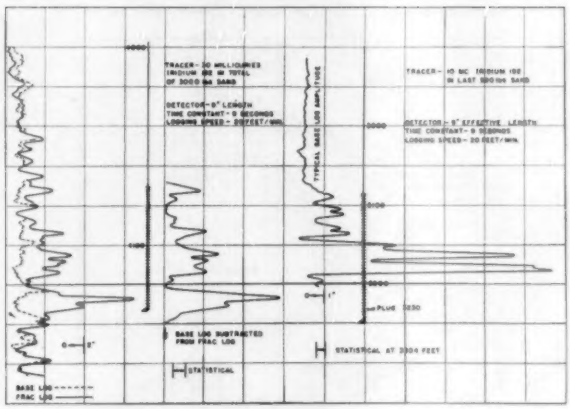

FIG. 4
A: ACID FRAC TRACERS. B: OIL FRAC TRACERS.

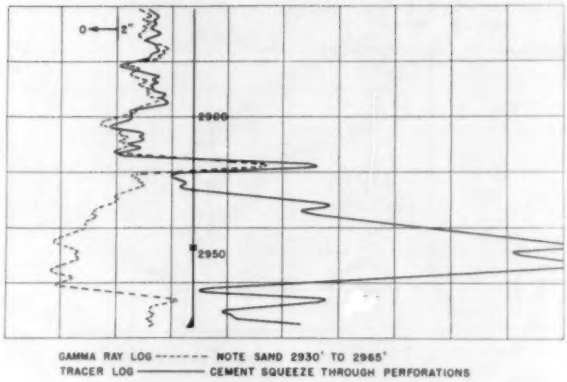

FIG. 5 — SQUEEZE CEMENT TRACER.

isotopes for these same problems has the advantages of a short half-life, allowing future radioactivity surveys uninfluenced by the tracer, and a more compact tracer unit which can be handled with much greater safety.

LOST CIRCULATION[16]

In the primary stage of drilling, thief zones or zones of lost circulation frequently hinder operations. Such zones can be traced and localized by a radioisotope added to the drilling fluid. This simple method, low in comparative cost, can save thousands of dollars compared to past methods and provide data useful in the drilling of offset wells or deepening operations in any given area. This drilling application example, shown in Fig. 6, is of a wildcat well in San Patricio County of South Texas, which penetrated the Lower Frio where circulation was lost below the conductor pipe in 1,100 ft of open hole.

A frangible disk type bailer laden with a mixture of 0.45 millicuries radioactive casing compound No. 60 and viscous mud was lowered on a wire line to a point within the casing. The disk was shattered by a blasting cap and the bailer withdrawn leaving the radioactive mud in position. The gamma ray instrument was then lowered through the radioactive slug, and positioned at a point several hundred feet below. The mud column and the tracer slug were pumped downward passed the instrument at various times as the latter was continually lowered until no reaction was experienced. A gamma ray log of the region was then made which located the zone of entry in the open hole. Successive runs of the instruments are shown and, by correlation with the electric log, it was evident that the tracer was entering the sand above 8,260 ft. After remedial measures had been performed and drilling continued for a short time, circulation was again lost. The above procedure was repeated with 0.9 millicuries of radioactive casing compound. This second survey is shown in Fig. 6. The same zone was found to be taking the mud.

CASING LEAKS

Casing leaks can be located by radioactive tracer techniques if the material can be pumped down the hole on top of a plug or into open hole. The flaws or breaks in the pipe or collars, if they allow a passage to the injection fluid, will normally concentrate particle-type tracers so as to permit detection with radioactivity logs.

The results shown in Fig. 7 are from a water injection profile survey. The two zones taking fluid through casing leaks at 2,326 ft and 2,396 ft show up prominently although most of injection was in the open hole.

CEMENT TOP LOCATION

Fig. 8 shows the results obtainable using a radioactive additive to cement for cement top location. In this particular case 20 lb (0.6 millicuries) of radioactive casing compound No. 60 was added to the first few sacks in the cementing of the original oil string. After the cement had set, a 4¾-in bit was run to bottom to condition the mud and check the plug. No scraper was run. Correlation between the radioactivity log and the potential curve of the electrical log showed the clear definition of the cement top at 5,039 ft. This correlation method was used since no gamma ray base log was available. The 13-ft spread between the high and low radiation at the cement top can be accounted for by a depth constant (logging speed times time constant) of 40 in and a detector length of 36 in. Also, a few feet of gradient to the tracer material could account for some of the effect. It is noteworthy that, in spite of the trailing of the tracer material below the cement top, the sands shown by the electric log are clearly evident on the gamma ray tracer log. These sands are shown in heavier lines on the tracer log.

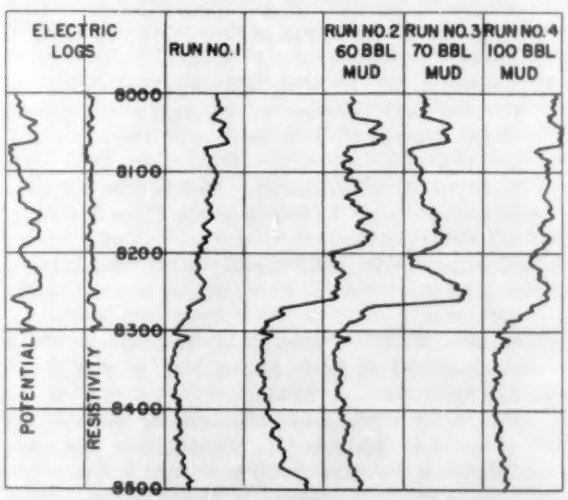

FIG. 6 — LOST CIRCULATION TRACER.

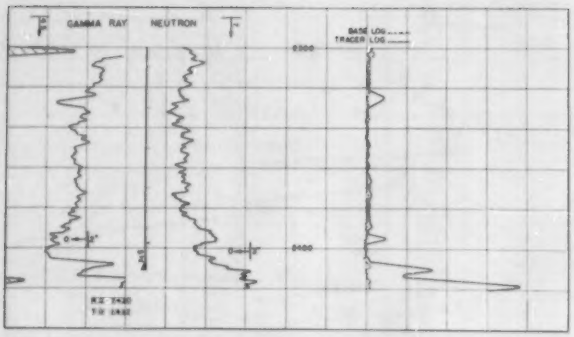

FIG. 7 — CASING LEAK LOCATION.

By using a radioisotope of about 5 millicuries a much finer resolution would be obtainable since an instrument having a shorter detector could be used for the tracer location. Also, using a short lived radioisotope such as Iodine 131 with an eight-day half-life, a natural gamma ray log could be obtained at any time after about seven weeks. Fig. 5, previously discussed, shows an example of Iodine 131 added to cement.

CONCLUSIONS

Radioactive tracers in their present state of development and field use add to established logging services a superior method of answering certain subsurface problems. They also add a very detailed picture of subsurface phenomena which, the authors feel, are less conclusively defined by temperature and spinner type surveys. Radioactive tracer logging not only supplements the older techniques but also adds considerably to the available tools of the petroleum industry.

ACKNOWLEDGMENTS

The authors wish to acknowledge the cooperation of the various oil companies that have aided in the tracer projects illustrated and released the logs for this paper.

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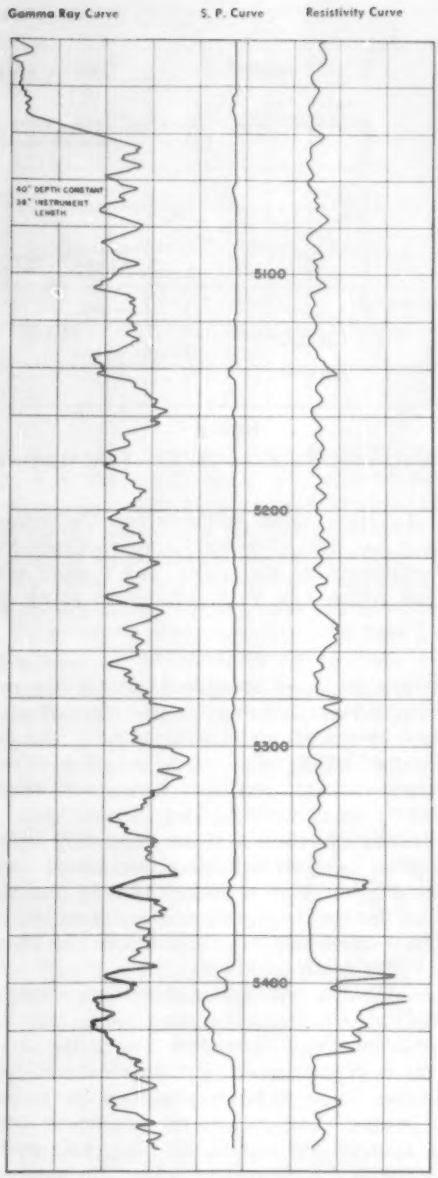

FIG. 8 — CEMENT TOP LOCATION.

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OIL RECOVERY PERFORMANCE of PATTERN GAS or WATER INJECTION OPERATIONS from MODEL TESTS

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ABSTRACT

A series of both water and gas pattern floods was made in the laboratory to study the oil recovery performances of such operations. These tests were conducted on consolidated sandstone models, using oil, water, and gas. The model floods were scaled to reproduce field performance under gas and water five-spot injection. X-ray shadowgraphs permitted observation of the gross fluid movement within the models.

A method was developed for applying the mobility ratio concept to water flooding and dispersed gas drives in a five-spot well pattern. The areal sweep efficiency at breakthrough for dispersed gas drives is much higher than previously expected, lying in the range of 50 to 100 per cent.

A method is presented for predicting the water-oil ratio performance of five-spot pattern water floods in uniform sands. This method is verified experimentally for the condition of no free gas initially present and for values of gas saturation normally encountered in fields following depletion operations. Production performance for pattern gas injection is also predictable by this method.

INTRODUCTION

In field pattern water flooding or dispersed gas injection operations, the displacing fluid (water or gas) is injected and oil is produced through wells which are, area-wise, small openings in a large container or reservoir of oil. As a result, not all of the area between the injection and producing wells is necessarily contacted by the injected fluid by the time it first reaches the producing wells. The question arises in predicting oil recovery, as to what fraction of the pattern area involved is contacted by either the injected water or gas due to the relative position of the injection and producing wells. This is the areal sweep efficiency. It is also desirable to know how well arrangement affects the oil production performance.

A solution to this problem has been attempted by many means. Mathematical analysis[1,2,3], and electrolytic models[4], have been used to establish a *breakthrough* areal sweep efficiency of 73 per cent for a five-spot pattern in which the ability of the oil to flow ahead of the invading fluid is equal to the ability of the invading fluid to flow in the invaded zone. All of these studies simulate only one of many field conditions.

Improved studies of areal sweep efficiency at breakthrough were made using the fluid mapper[5], potentiometric models[6], and X-ray shadowgraph techniques[7]. In these it was possible to study the effect of variations in mobility of the injected and displaced fluids, and so to cover a wide range of field conditions. The limitation of these studies is that, with these models, it was not possible to simulate the saturation gradient behind the flood front when oil is displaced by gas or water.

In the most recent published technical paper[8] on the subject, a method was presented for predicting the oil recovery performance after breakthrough in a five-spot pattern water flood. The method involved correlations which were obtained experimentally using miscible fluids. One limitation of this work was that a saturation gradient, usually found in immiscible fluid displacement, was absent in these studies. Also the laboratory studies did not cover the situation of a water flood following oil recovery by depletion drive, as is the situation in most field water floods.

The tests reported in this paper were made using oil, water, and gas, thus eliminating the simplifications of former studies. Also reported are laboratory studies on

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[1]References given at end of paper.

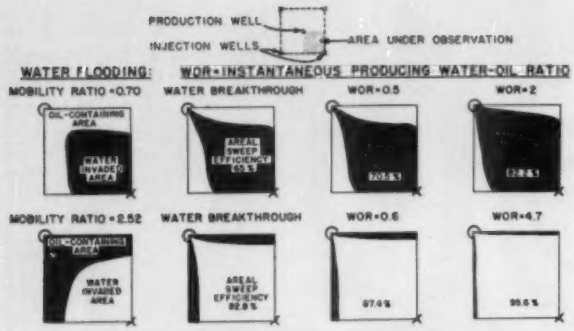

FIG. 1 — X-RAY SHADOWGRAPHS OF FLOOD PROGRESS FIVE-SPOT PATTERN.

For Mobility Ratio = 0.70, Tracer in Water Phase
For Mobility Ratio = 2.52, Tracer in Oil Phase

areal sweep efficiency of a five-spot pattern involving oil displacement with gas. All of the present studies have been made under conditions which simulate field operations in uniform sands in which there is no appreciable gravity segregation of the fluids.

MATERIALS AND EQUIPMENT

MODELS

A five-spot pattern has a producing well surrounded by four injection wells. This pattern area can be considered as four equal quadrants. The gas and water injection studies were made using a model representing a quadrant of a five-spot pattern. The model was made from a slab of consolidated sandstone, 4 in square and ¾ in thick. The surface pores of the rock were sealed with Phenoline 300, a phenol-formaldehyde plastic, to confine fluid flow to the internal pore spaces. This plastic is completely resistant to the particular fluids used in these tests. An injection well was placed at one corner of the model and a production well at the opposite corner as shown in Fig. 1.

The laboratory pattern water floods were made using models constructed of Torpedo sandstone (400 mds, 24.6 per cent porosity). The laboratory gas injection tests were made on models of both Torpedo and Bandera sandstone (10 mds, 15 per cent porosity). Both of these rock materials were obtained from surface outcrops.

FLUIDS

The fluids used in the laboratory pattern water floods were oil, water, and butane. In order to identify the location of water and oil in the rock, one of these was "tagged" with an iodine compound which absorbs X-rays. To "tag" one of the fluids, either from 15 to 30 per cent iodobenzene by volume was added to the oil, or the water was half-saturated with sodium iodide. In order to have the laboratory floods properly scaled to typical field conditions, it was necessary to have reduced interfacial tension between the oil and water. This was accomplished by adding isopropyl alcohol to both the oil and water. The treated oil and water had an interfacial tension of less than 3 dynes/cm compared to 38 for the untreated fluids.

The oils used were refined products. Oils of various viscosities were made by blending different oils, including castor oil, mineral oil, and C_{10}-C_{12}. The water used was either 0.25 N sodium chloride solution or half-saturated sodium iodide solution.

The fluids used in the laboratory pattern gas injection tests were oil and gas. The oils were iso-octane, C_{10}-C_{12} or blends of C_{10}-C_{12} and mineral oil. The gas was either air or butane. Air was the injected gas in all the gas injection floods. Butane was dissolved in oils where it was desirable to simulate a high shrinkage crude.

X-RAY APPARATUS

The X-ray tube used was of the type commonly used in medical diagnostic work. The tube was mounted inside a lead-lined cabinet, the target placed so that the X-ray beam was directed upward.

With the rock model set above the X-ray tube, the gross position of the water and oil in the model could be recorded on photographic film, or observed using a fluoroscopic screen.

The X-ray shadowgraphs are used to provide quantitative data as to the area contacted by the injected water at any time in the pattern water floods.

PROCEDURE

In preparing the models for testing, two different procedures were used depending upon whether water or gas injection was to be studied. For waterflood tests the pores of the rock were first fully filled with water. By oil flooding, the water content was reduced to a simulated connate water saturation. In the gas injection tests the pores of the rock model were completely filled with an oil. No connate water was simulated.

Pattern flooding by either gas or water may be applied to an oil reservoir following oil recovery by depletion drive. To simulate this condition in the laboratory a butane-oil solution was placed in the model under pressure. Reduction of pressure resulted in a depletion drive, the evolved butane gas driving the oil and also causing the oil to shrink. Gas saturation after the depletion drive was controlled by varying the butane content of the original oil.

WATER INJECTION

Water was injected into the models by constant rate pumps. At the water injection rates used, the corresponding injection pressure was sufficient to redissolve all of the butane gas in the model behind the flood front. This condition simulates that encountered in most field waterflooding operations. Progression of the water flood was observed on a fluoroscopic screen. The instant of water breakthrough was detected electrically. At critical stages in the flood, X-ray shadowgraphs were taken. Fig. 1 shows typical shadowgraphs taken during two five-spot water floods. Other data taken in all water floods include the volume of water injected and the volumes of oil and water produced, at approximately 1 per cent pore volume increments in oil production.

GAS INJECTION

Gas was injected into the models at constant pressure. Because of the low gas saturations present in the gas invaded area, it was not possible to obtain sufficient contrast with X-ray shadowgraphs to evaluate areal sweep efficiency by this method. The value of the breakthrough areal sweep efficiency by gas injection was calculated by a method discussed later in this paper.

MODEL SCALING

In the laboratory small models are used to study what happens in a large reservoir. These models must be a replica in every necessary way of an oil field, in order for the test results to be of practical significance.

One limitation of this study is that the laboratory model represents an idealized system, in which there are no gravity effects, permeability stratification, or local fractures. The sandstone models used are uniform in permeability and of the same thickness throughout. The relative permeability characteristics of these models are typical of those of some oil-bearing formations. The tests covered a wide enough range of rock and fluid characteristics, injection rates, etc., to simulate a wide variety of field flooding conditions.

The ratio of the wellbore diameter to well spacing in the model is much greater than that ratio usually encountered in the field. It was not convenient to scale this ratio in the laboratory models. However, laboratory pattern floods involving models of different wellbore diameter-well spacing ratios have indicated that the ratio used in the models is sufficient to yield results applicable to field floods.

It is possible to determine the appropriate model fluid flow scaling criteria from the differential equation of the flow process. In order to scale the stabilized zone in the laboratory model to that in the field, if the model and reservoir are of the same rock and gas (or water) -oil viscosity ratio is the same in both, the following scaling criterion applies:

$$\left[\frac{q_i \mu_o x}{\gamma \cos \Theta}\right]_{\text{model}} = \left[\frac{q_i \mu_o x}{\gamma \cos \Theta}\right]_{\text{field}} \quad . \quad . \quad . \quad (1)$$

where q_i = injection rate per foot of pay
μ_o = oil viscosity
x = distance between wells
γ = oil-water (or gas) interfacial tension
Θ = contact angle of oil and water (or gas) interface with the rock surface

With the fluids and rates used, the laboratory model water floods were scaled to field floods with water injection rates of from 0.30 to 18.2 B/D per foot of pay thickness for 10-acre spacing or from 0.15 to 9.1 B/D per foot of pay thickness for 40-acre spacing. In the range of injection rates studied, there was no noticeable effect of rate upon oil recovery efficiency.

Addition of isopropyl alcohol to the oil and water results in a water viscosity greater than 1 cp. However, since the displacement pattern in water flooding is dependent upon the water-oil viscosity ratio, the model floods are equivalent to field floods of the same viscosity ratio.

It is not practical to reduce the interfacial tension between gas and oil. Thus, in order that the scaling criterion set up in Equation 1 be fulfilled, it was necessary to perform these model gas injection floods at relatively high injection rates. The range of laboratory gas injection rates was equivalent to 0.1 to 0.6 MCF/D/ft of pay thickness at the injection conditions. This corresponds to approximately 3.5 to 21 standard MCF/D/ft at 500 psig injection pressure.

RESULTS AND DISCUSSION

Areal Sweep Efficiency at Breakthrough

Realizing that there is a saturation gradient when water displaces oil, tests were run with these fluids to see if the breakthrough areal sweep efficiency versus mobility ratio would correlate with the data of Dyes et al[5]. The mobility ratio was calculated assuming that the relative permeability to water in the invaded zone was the same throughout, i.e., the value at residual oil saturation. The results calculated in this manner were not in agreement with the published correlation, especially in the lower range of calculated mobility ratios. It was recognized that, in immiscible fluid flooding, the injected fluid mobility constantly decreases from the injection well toward the flood front. Several methods were tried to arrive at a value for mean water permeability that would describe the over-all water conductivity in the invaded area. The scheme that proved satisfactory was to use the water relative permeability at the average water saturation behind the stabilized zone. This can be determined for a system by using appropriate relative permeability characteristics and fluid properties, and an adaption of the Buckley and Leverett frontal drive equation[6]. This scheme for calculating mobility ratio brought the results of pattern waterflood tests into agreement with the correlation published by Dyes et al.

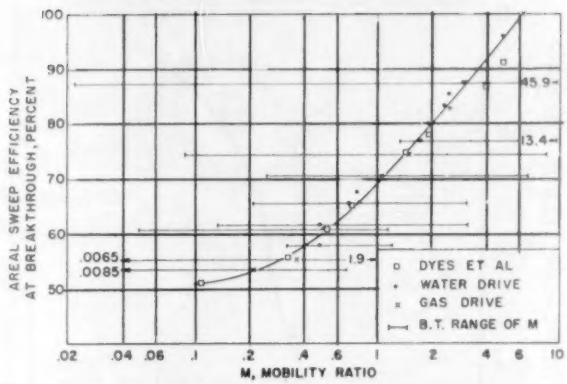

FIG. 2—AREAL SWEEP EFFICIENCY AT BREAKTHROUGH—FIVE-SPOT WELL PATTERN.

Although there is no theoretical justification apparent for using this method of calculating mobility ratio, the fact that the results using water and oil agree with those using miscible fluids leads to the conclusion that the method is satisfactory for calculating mobility ratio for the displacement of oil by an immiscible fluid. In miscible fluid flooding there is no saturation gradient behind the flood front. Therefore, the permeability to the injected fluid is the same from the injection well to the interface of the fluids.

In Fig. 2 is shown the experimentally determined correlation of areal sweep efficiency at breakthrough versus mobility ratio, obtained using immiscible fluids. In addition, the miscible fluid test results of Dyes et al are shown for comparison.

Values of areal sweep efficiency at breakthrough were obtained by measuring, from the X-ray shadowgraphs, the fraction of the total pattern area contacted by water at breakthrough. Using oil and water with reduced interfacial tensions resulted in sharp contrast on the shadowgraphs between the invaded and uninvaded zones (see Fig. 1). Fingering of fluids was not a problem as when using miscible fluids. It was found that the oil recovery to water breakthrough could be predicted from the breakthrough areal sweep efficiency

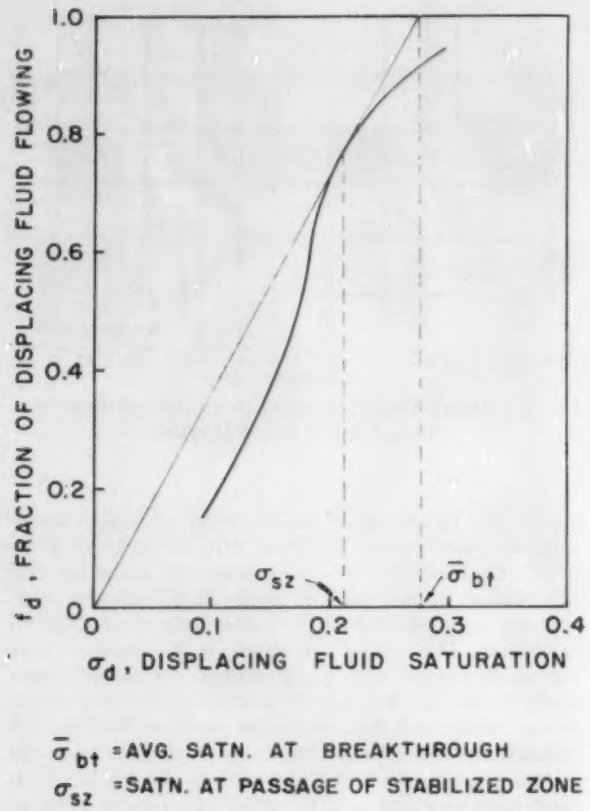

FIG. 3—CALCULATION OF AVERAGE DISPLACING FLUID SATURATION AT BREAKTHROUGH.

and the average water saturation in the invaded zone, calculated using the Buckley and Leverett method. This method proved very useful in determining breakthrough areal sweep efficiency for dispersed gas drives, since this could not be measured using present X-ray shadowgraph techniques. The areal sweep efficiency at breakthrough for five-spot gas drives was calculated by comparing the oil actually recovered at breakthrough to the theoretical oil recovery at breakthrough, assuming 100 per cent sweep efficiency. In Fig. 2 will be noted that the data for gas drives agree with those for water floods. Of significant interest is the fact that the breakthrough areal sweep efficiencies for gas drives are in the same range as those for water floods. This was not expected before the study, based on calculated gas drive mobility ratios which did not take into account saturation gradients. Although the areal sweep efficiencies may be the same for gas and water drives, the volume of oil recovered to breakthrough will be less for gas injection, due to the lower gas saturation in the invaded area at breakthrough.

The ends of horizontal lines through the immiscible fluid data points of Fig. 2 represent the range of mobility ratios that can be computed for each of the systems. The far left point assumes, for calculation purposes, that only minimum residual oil remains in the invaded zone. The points to the far right are those for the mobility ratios calculated using the invading fluid mobility at the saturation immediately behind the stabilized zone. It is obvious that neither of these methods for calculating the invading fluid mobility provide satisfactory correlation.

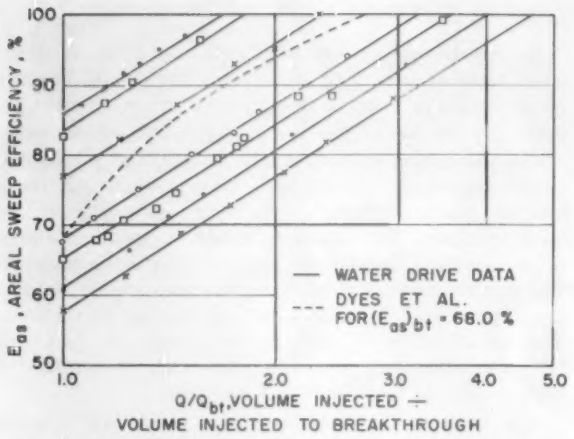

FIG. 4—INCREASE IN AREAL SWEEP EFFICIENCY AFTER BREAKTHROUGH.

The method for calculating the useful value of mobility ratio for immiscible fluids is as follows: (the data needed are appropriate relative permeability characteristics and fluid properties).

1. The average saturation behind the flood front is determined by constructing a plot of f_d, the fraction of the displacing fluid flowing, versus σ_d, the displacing fluid saturation, as shown by various authors[9,10,11,12]. Then draw a straight line, whose origin is the original displacing fluid saturation, tangent to the f_d-σ_d curve. Extend this straight line to $f_d = 1.0$. The saturation at this point is the average invading fluid saturation at breakthrough (see Fig. 3).

2. Read the value of relative permeability to the invading fluid, k_d, at this average saturation from the appropriate relative permeability curve.

3. The relative permeability to oil, k_o, is the value corresponding to the oil saturation ahead of the flood front.

4. $M = \frac{k_o}{\mu_o} \cdot \frac{\mu_d}{k_d}$.

AREAL SWEEP EFFICIENCY AFTER BREAKTHROUGH

A large fraction of the total recoverable oil may be obtained after breakthrough. In order to predict the oil recovery performance after breakthrough, the manner in which the areal sweep efficiency increases after breakthrough must be known. Laboratory waterflood tests were continued to a producing water-oil ratio in excess of 20:1. Examples of the increase in areal sweep efficiency after breakthrough are shown in Fig. 1. Fig. 4 shows experimental data on the areal sweep efficiency after breakthrough for several water floods as measured from the X-ray shadowgraphs. As indicated by Fig. 4, the areal sweep increases linearly with the logarithm of Q/Q_{bt}, where Q is the injected fluid volume at any time and Q_{bt} is the volume to breakthrough. Despite the fact that a wide range of flow characteristics are represented, all the curves shown in Fig. 4 have the same slope. This same variation of areal sweep efficiency after breakthrough with continued injection was found to hold for dispersed gas drives.

It is possible to obtain from miscible fluid flood data[5], the manner in which the areal sweep efficiency increases with the ratio Q/Q_{bt}. A typical set of data

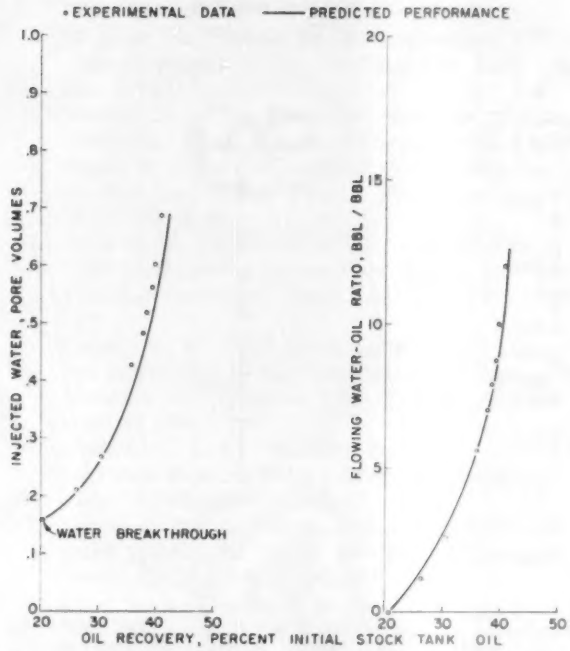
• EXPERIMENTAL DATA
PREDICTED PERFORMANCE
INJECTED WATER, PORE VOLUMES
FLOWING WATER-OIL RATIO, BBL / BBL
WATER BREAKTHROUGH
OIL RECOVERY, PERCENT INITIAL STOCK TANK OIL

FIG. 5 — FIVE-SPOT WATER INJECTION PERFORMANCE.

2.25 cp Water — 102 cp Oil
Mobility Ratio = 0.480
E_{as} AT WBT = 57.9 Per Cent

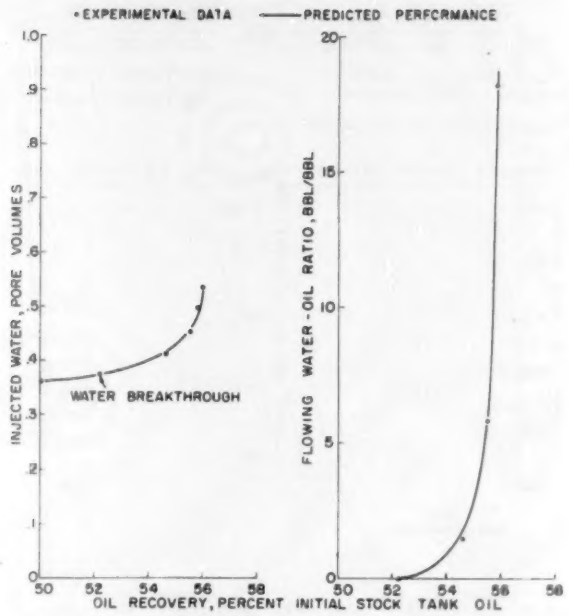

FIG. 6 — FIVE-SPOT WATER INJECTION PERFORMANCE PARTIAL DEPLETION.

Initial Gas Saturation = 6.1 Per Cent P.V.
2.70 cp Water — 6.17 cp Oil
Mobility Ratio = 4.91 E_{as} AT WBT = 96.8 Per Cent

is shown in Fig. 4. The disagreement, shown for the case in which the breakthrough areal sweep efficiency is 68 per cent, is typical of that for other mobility ratios. The difference may be explained by the fact that in miscible floods the mobility in the invaded area remains constant for the duration of the flood. In immiscible floods in which there is a saturation gradient behind the flood front, the mean injected fluid mobility in the invaded area increases after breakthrough, as the invaded area is swept to a lower oil saturation. This exhibits a point in which the miscible pattern floods are not representative of most immiscible floods.

EFFECT OF INITIAL FREE GAS SATURATION IN WATER FLOODING

Many waterflooding projects are applied to reservoirs which have been partially depleted by primary means. It is of practical importance to determine the effect of this gas saturation upon oil recovery performance by water drive. The experimental studies covered by this paper were for the situation in which none of the initial gas saturation is trapped behind the flood front.

In all of the experimental model water floods having initial gas saturation, there was no oil production until liquid fill-up of the gas space. At some stages of a pattern flood, the original circular front distorts and cusps towards the production wells. If fill-up is accomplished before the flood front cusps, the breakthrough areal sweep efficiency will be the same as if no free gas had been present initially. The performace after breakthrough also will be the same, with the exception that less oil, equal to volume of the initial free gas saturation, will be produced at any injected volume in the flood following partial depletion. The experimental work demonstrated that for almost all waterflooding conditions, fill-up is accomplished before the flood fronts cusp and hence does not affect areal sweep.

EFFECT OF INITIAL GAS SATURATION IN DISPERSED GAS INJECTION

It was postulated that the area contacted by gas would be 100 per cent at the start of gas injection if gas saturation prior to the start of gas injection were high enough to form a connected gas permeability throughout the pattern area. If this were true, the oil recovery performance of a five-spot pattern system should be the same as that of a linear system. To check this, the gas-oil relative permeability characteristics, as determined from production data on the pattern models were compared to those of a linear system composed of the same materials. Initial gas saturations ranging from 4 to 44 per cent pore volume, created by a solution drive, were used. In all cases the results agreed within experimental error. This is taken to mean that the assumption of 100 per cent areal sweep efficiency is satisfactory for practical purposes.

PREDICTION OF OIL RECOVERY PERFORMANCE, FIVE-SPOT PATTERN

Dyes et al[8] suggested a scheme for predicting the oil recovery performance from a fully liquid saturated five-spot pattern. Simply stated, the production during an interval of time after breakthrough is considered to come from two regions, namely, the previously and the newly-invaded portions of the pattern. Although the general outline for the method was presented by Dyes et al, certain details have been added to predict waterflood and especially gas drive performance. This expanded method of prediction is outlined as follows:

The oil and water (or gas) produced from the previously invaded portion of the five-spot pattern at any time is calculated using the Buckley and Leverett frontal drive equation as modified by Welge[11]. In an ideal linear system the term Q_i is defined by Welge as

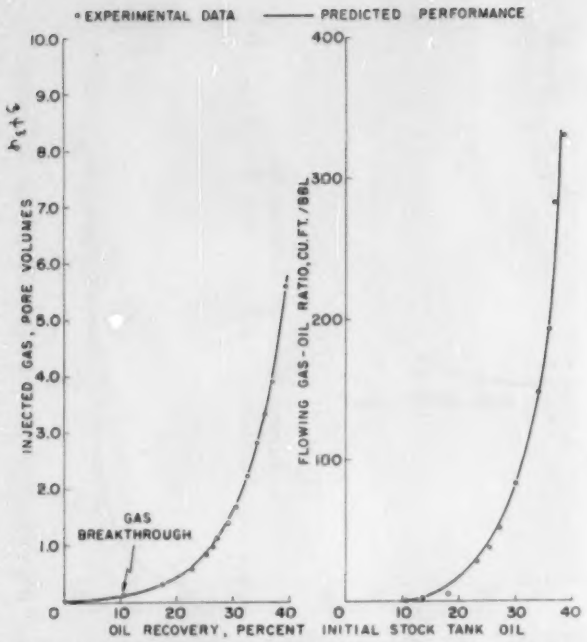

FIG. 7 — FIVE-SPOT GAS INJECTION PERFORMANCE.
0.0182 cp Gas — 1.43 cp Oil
Mobility Ratio = 1.5
E_{as} AT GBT = 74.3 Per Cent

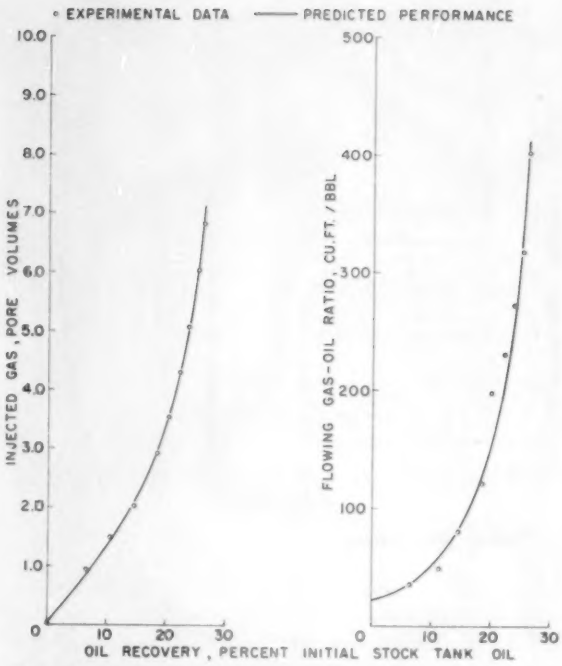

FIG. 8 — FIVE-SPOT GAS INJECTION PERFORMANCE FOLLOWING PARTIAL DEPLETION.
Initial Gas Saturation = 18.1 Per Cent P.V.
0.0182 cp Gas — 1.17 cp Oil
E_{as} AT GBT = 100 Per Cent

the cumulative injected volume in terms of total pore volume of the system. In a pattern flood the pore volume involved with injected fluid increases as the areal sweep increases. Therefore, the term Q_i has been modified to take into account the continual increase in the portion of the pattern invaded. The calculation can be done in a step-wise manner and is illustrated in the Appendix.

The oil produced from the newly invaded portion of the five-spot pattern is determined from the rate of increase in areal sweep efficiency with injected volume (shown in Fig. 4) and the decrease in oil saturation in this newly invaded portion. The decrease in oil saturation is equal to the increase in injected fluid saturation immediately behind the stabilized zone. This saturation is found from a f_d vs σ_d plot for the system invaded, and is the saturation at the tangent to the curve, as illustrated in Fig. 3.

To obtain the instantaneous producing ratio of water and oil (or gas and oil) at any time or at any volume of injected fluid, the contributions from the previously invaded and newly invaded areas are summed. Appendix I presents a working form of this method of calculation.

The above method considers the system initially liquid filled. The performance to breakthrough for a liquid filled system is straightforward. For cases of initial gas saturation prior to water flooding, the oil recovery to breakthrough and at subsequent times is less by the volume of initial gas saturation. For cases of initial gas saturation prior to gas injection, the oil recovery performance is that calculated for a linear system whose pore volume is that of the pattern and having the same value of initial gas saturation.

Figs. 5 through 8 are typical comparisons between predicted and observed oil recovery performance. The agreement illustrates the utility of the method of calculation for dispersed gas drives and water floods with and without previous primary oil recovery.

Although the pattern floods were made on only two consolidated sandstones, in effect different rock flow characteristics were involved. The addition of isopropyl alcohol to the oil and water caused a wettability effect, resulting in different relative permeability characteristics for the different combinations of fluids used. Although the change in wettability could not be quantitatively determined, the effect on fluid flow behavior could be determined by relative permeability measurements. Typical sets of relative permeability characteristics involving the fluids used are shown in Fig. 9. Despite the variation in relative permeability characteristics, the actual and predicted performance agree satisfactorily.

It should be realized that the method of prediction applies precisely only to uniform sands, and systems in which gravity effects are of no major significance.

CONCLUSIONS

1. A method has been developed for applying the mobility ratio concept to water flooding and dispersed gas drives in a five-spot well pattern. The areal sweep efficiency at breakthrough for dispersed gas drives is much higher than previously considered, lying in the range of 50 to 100 per cent.

2. The oil recovery performance of a five-spot water flood or dispersed gas drive in an idealized system can be predicted using appropriate rock and fluid characteristics together with experimentally determined correlations, by a modification of the Buckley and Leverett frontal drive equation.

ACKNOWLEDGMENTS

Appreciation is expressed to J. D. Ireland, R. E. Gladfelter, W. E. Lamoreaux, and R. E. Lewis for their contributions and help in collecting the experimental data.

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APPENDIX

METHOD OF CALCULATION OF FIELD FIVE-SPOT WATER OR GAS INJECTION PERFORMANCE

Table 1 gives suggested columnar headings which may be used in calculating the oil recovery performance of a five-spot water flood or gas drive.

An example calculation is given for a hypothetical waterflood project. The physical charactertistics of this field are as follows:

1. Relative permeability characteristics as shown by the short-dashed lines in Fig. 9.
2. Oil viscosity 10.0 cp, water viscosity 1.0 cp.
3. Gas saturation by primary recovery—10 per cent pore volume.
4. Connate water saturation — 26.0 per cent pore volume.
5. 40-acre spacing.
6. Thickness—20 ft.
7. Porosity—24 per cent.
8. Oil reservoir volume factor at the flooding pressure—1.100.
9. Water injection rate—300 B/D per well.

The first step is the calculation of the average water saturation in the invaded zone at breakthrough, $\overline{\sigma}_{wbt}$, and the water saturation at the passage of the stabilized zone, σ_{wss}. This is done as shown in Fig. 3.

The relative permeability to water at $\overline{\sigma}_{wbt}$ is obtained from the appropriate relative permeability characteristics of the formation rock.

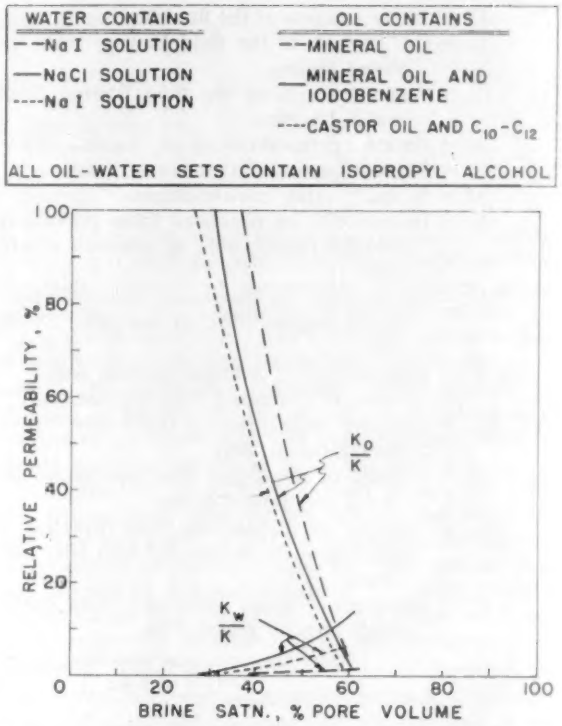

FIG. 9 — WATER-OIL RELATIVE PERMEABILITY CHARACTERISTICS, TORPEDO SANDSTONE INVOLVING LABORATORY FLUIDS USED IN PATTERN FLOOD STUDIES.

The mobility ratio, M, for the flood is calculated, using the relative permeability to water at $\overline{\sigma}_{wbt}$, obtained in the previous step.

The areal sweep efficiency at breakthrough, $(E_{as})_{bt}$, is read from Fig. 2 at the calculated value of mobility ratio.

The manner in which the areal sweep efficiency changes with continued water injection is obtained from Fig. 4. For a system under consideration, construct a straight line parallel to the other lines through the value of $(E_{as})_{bt}$ at $\frac{Q}{Q_{bt}}$ equals 1.0.

The water drive calculation outline shown in the tabulation may be modified to apply to dispersed gas drive operations by: (1) changing all subscripts signifying water to those for gas, and (2) adding the gas expansion term to Column 19 (which becomes gas-oil ratio).

The Nomenclature for the tabulation follows this Appendix.

It should be noted in the example water drive calculation the oil produced from the previously swept region, (Column 15) is small compared to the total oil production (Column 17). This is not always the situation, especially in gas drives where the oil production coming from the previously invaded area can be the major portion of the total.

NOMENCLATURE

E_{as} = Areal sweep efficiency, fraction.

$(E_{as})_{bt}$ = Areal sweep efficiency at time of breakthrough of injected fluid into producing well, fraction.

f_o = Oil fraction of the fluid flowing.

f_w = Water fraction of the fluid flowing.
f_{oz} = Oil fraction of the fluid flowing from invaded region.
f_{wz} = Water fraction of the fluid flowing from invaded region.
k_o = Relative permeability to oil, fraction.
k_w = Relative permeability to water, fraction.
M = Mobility ratio, dimensionless.
N_p = Incremental oil produced from previously invaded region, bbls. at reservoir condition.
N_a = Incremental oil produced from newly-invaded region, bbls. at reservoir condition.
$P.V.$ = Pore volume of five-spot pattern, bbls.
Q = Volume of displacing fluid injected, bbls.
Q_{bt} = Volume of displacing fluid injected to breakthrough, bbls.
Q_i = Volume of displacing fluid injected, in invaded area pore volumes.
Q_{ibt} = Volume of displacing fluid injected to breakthrough, in invaded area pore volumes.
W_p = Incremental water produced from previously invaded region, bbls.
WOR = Water-oil ratio, bbls. water per bbl. stock tank oil.
β = Reservoir volume factor, dimensionless.
μ_o = Oil viscosity, cp.
μ_w = Water viscosity, cp.
σ_{cw} = Connate water saturation, fraction pore volume.
$\bar{\sigma}_{gi}$ = Average initial gas saturation, fraction pore volume.
$\bar{\sigma}_o$ = Average oil saturation, fraction pore volume.
$\bar{\sigma}_{obt}$ = Average oil saturation at breakthrough, fraction pore volume.
σ_{wz} = Water saturation at producing end of invaded portion, fraction pore volume.
$\bar{\sigma}_{wbt}$ = Average water saturation at water breakthrough, fraction pore volume.
σ_{wsz} = Water saturation at passage of stabilized zone, fraction pore volume.
$\sigma\nabla_w$ = Difference between average water saturation in invaded zone and water saturation at producing well, fraction pore volume.

Subscript *inv* indicates value of term in invaded area.

TABLE 1 — TABULATION WORKSHEET FOR PREDICTION OF FIVE-SPOT PATTERN WATER INJECTION

$\bar{\sigma}_{wbt} = 0.590$; $\sigma_{wsz} = 0.560$; k_w at $\bar{\sigma}_{wbt} = .065$; $M = 1.55$; $(E_{as})_{bt} = 76.0$ Per Cent

1	2	3	4	5	6	7	8	9	10	11
Q/Q_{bt}	Q_{bt} Reservoir bbls.	Q Reservoir bbls.	ΔQ Reservoir bbls.	E_{as} Fraction	ΔQ_i Pore Vol.	Q_i Pore Vol.	$\left(\frac{df_w}{d\sigma_w}\right)_{\sigma_{wz}}$	σ_{wz} Fraction	f_{wz} Fraction	f_{oz} Fraction
Select initially as 1.000, then add maximum increments of 0.100. Smaller increments yield more accurate results.	$Q_{bt} = (\bar{\sigma}_{wbt} - \sigma_{cw})(E_{as})_{bt}(P.V.)$	(Col. 1) × (Col. 2)	Difference between present value of Q and that in previous step.	Construct line on Fig. 4 which applies to $(E_{as})_{bt}$ for system. Read values of E_{as} for values of Col. 1.	(Col. 4) ÷ [(Col. 5) × (P.V.)]	Q_i at $Q/Q_{bt} = 1.000$ equals $(\bar{\sigma}_{wbt} - \sigma_{cw})$; Subsequent values of Q_i obtained by adding present value of ΔQ_i to previous value of Q_i.	1.0 ÷ (Col. 7); (see Reference 11)	Value of σ_w which has $df_w/d\sigma_w$ equal to Col. 8. Plot of $df_w/d\sigma_w$ obtained from relative perm. characteristics and fluid viscosities.	Value of f_w at σ_{wz}	1.0 − (Col. 10)
1.000	374,000	374,000	—	.760	—	.330	3.03	.560	.924	.076
1.100	374,000	411,400	37,400	.788	.0318	.362	2.76	.580	.972	.028
1.200	374,000	448,800	37,400	.813	.0309	.393	2.54	.584	.981	.019
1.300	374,000	486,200	37,400	.835	.0301	.423	2.36	.597	.989	.011

CONTINUATION OF TABULATION WORKSHEET

12	13	14	15	16	17	18	19	20	21	22
$\Delta_1 E_{as}$ Fraction	N_a Reservoir bbls.	$N_p + W_p$ Reservoir bbls.	N_p Reservoir bbls.	W_p Reservoir bbls.	$N_a + N_p$ Reservoir bbls.	Incr. Oil Prod. STB	Avg. WOR Over Incr. bbl/bbl	Cum. Oil Rec. By Water Flood, STB	Time After Start Of Inj. days	Oil Prod. Rate After Fill-up B/D
Difference between present and previous value of E_{as} (Col. 5).	(Col. 12) × $(\sigma_{wsz} - \sigma_{cw})$ × (P.V.); σ_{wsz} found as shown in Fig. 3.	(Col. 4) − (Col. 13)	(Col. 11) × (Col. 14)	(Col. 14) − (Col. 15)	(Col. 13) + (Col. 15)	(Col. 17) ÷ β	(Col. 16) ÷ (Col. 18)	Previous value of Col. 20 + present value of Col. 18	(Col. 3) ÷ Avg. Injection rate	Slope of Curve of Col. 20 vs. Col. 21
								204,600*	1,247	300
.028	12,500	24,900	700	24,200	13,200	12,000	1.61	216,600	1,372	96.3
.025	11,200	26,200	500	25,710	11,690	10,610	2.20	227,210	1,497	85.2
.022	9,850	27,550	303	27,247	10,153	9,247	2.69	236,457	1,621	74.1

*Value of Col. 20 at $Q/Q_{bt} = 1.000$ equals $\left[(\bar{\sigma}_{wbt} - \sigma_{cw})(E_{as})_{bt} - (\bar{\sigma}_{gi})\right] \times \frac{(P.V.)}{\beta}$

★★★

DISCUSSION

A. B. DYES
MEMBER AIME

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This paper raises several interesting points about the effect of a mobility gradient on displacement efficiency. Two or three minor questions come to mind which might deserve further clarification:

This paper would be of more help to others engaged in similar studies if the analysis had included the effect on pattern behavior of a gradient in the true mobility of the swept region. The analysis of the experimental results presented by the authors illustrates the influence of a gradient in the mobility of only the displacing phase. The true mobility at a given point in the swept region is the sum of the mobility of both the displacing as well as the displaced phase. It is the gradient in this total mobility that controls the pattern behavior rather than a gradient in the mobility of only the displacing phase. The authors have not drawn a comparison between these mobilities. The omission of the gas-oil permeability relationships of these experiments and the inclusion of only typical water-oil permeability relationships prevents the reader from making this comparison.

In this study, the authors assume that the gradient in mobility which is established in the swept portion of the model can be calculated through the use of a relative permeability curve and the method of Buckley-Leverett. In a study of this type, it is desirable that this assumption be confirmed by direct measure of the saturation in the swept region. The use of alcohol mixtures of low interfacial tension and the fingering which occurs in gas injection experiments in this type of model presents a very real likelihood that the mobility gradient conditions attained in the flooding of the models are at variance with those calculated.

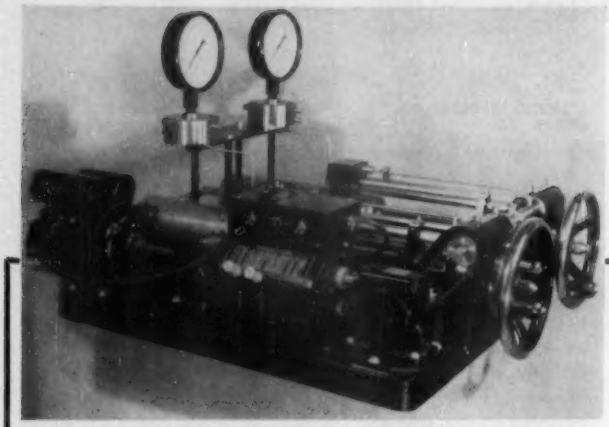
For the case in which gas is injected into a reservoir containing a high gas saturation, this article postulates that 100 per cent of the pattern is invaded at gas breakthrough. The agreement in the performance between the flood of linear and a five-spot model is cited as a substantiation that this is the case. While gas is flowing throughout this type reservoir at the time gas injection is begun, the gas breakthrough which is of concern to the operator as well as to the experimentalist should be the condition at which the producing gas-oil ratio begins to rise. This condition occurs when the first line of saturation change reaches the producing well. The movement of this saturation line through the model cannot proceed in a more favorable manner than that dictated by a mobility ratio of 1 (mobility behind this saturation line always increasing). This would call for a pattern at breakthrough in the five-spot of no more than 70 per cent. In the absence of fingering, the linear model behavior would be independent of mobility ratio and would show a sweep of 100 per cent of the pattern at breakthrough. The agreement between the behavior of the linear and five-spot laboratory models cited could result if fingering controlled the performance of both models. The theoretical interpretation of a 100 pattern efficiency at breakthrough is not supported. However, the movement of the lines of constant saturation through the model containing a high gas saturation would be expected to occur so rapidly after breakthrough that a practical treatment could well assume a linear flood in this type gas injection operation. ★★★

AUTHORS' REPLY TO A. B. DYES

A. B. Dyes' concern for the true mobility in the invaded pattern region was shared by the authors. However, it was found that taking into account the mobility of the displaced fluid in the invaded region did not significantly change the mobility ratio so calculated. This could be rationalized when considering that the correlation of areal sweep efficiency at breakthrough vs ratio is the same when using either immiscible or miscible fluids. With the latter there is only one phase flowing behind the flood front.

The authors did not feel it necessary to measure the saturation gradients in the invaded region of the models, since that would be primarily of academic interest. The purpose of the model floods was to determine if the over-all oil recovery performance could be predicted mathematically.

Dyes suggests that, in pattern gas drives following normal depletion operations, the areal sweep efficiency at breakthrough of *injected* gas is theoretically 70 per cent and not 100 per cent. Actually in this type of operation there is no practical interest in differentiating at the producing wells between injected gas and that which was in place at the start of injection. The significant point is that the production performance measured in scaled models is identical to that from a linear system under the same conditions. Therefore the areal sweep efficiency, controlled by well arrangement, does not enter into the prediction of oil recovery performance for gas injection following normal depletion. To have the method of calculation (presented in Appendix) suitable for all field conditions, the areal sweep efficiency is considered 100 per cent at start of gas injection following normal depletion. ★★★



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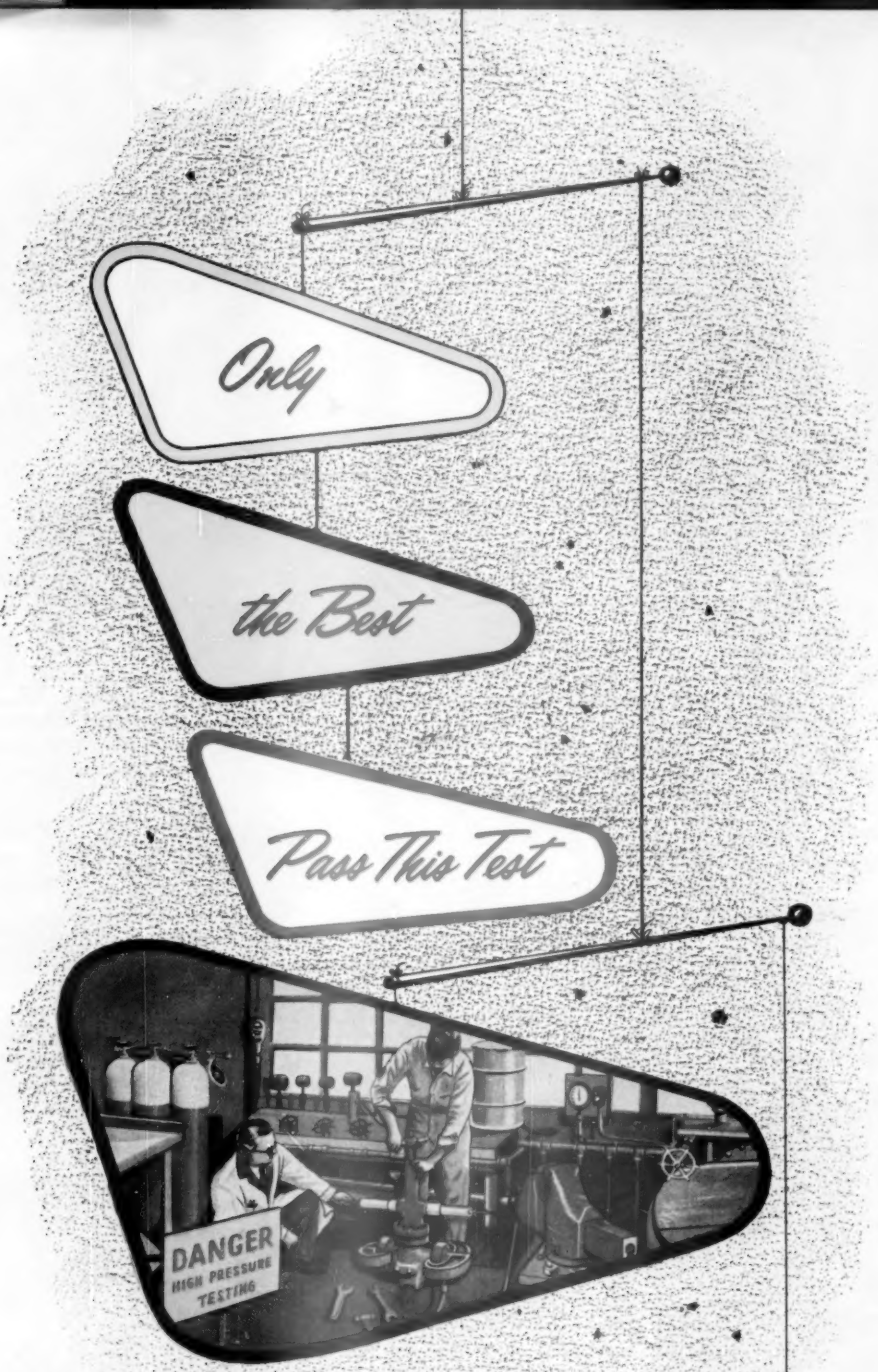

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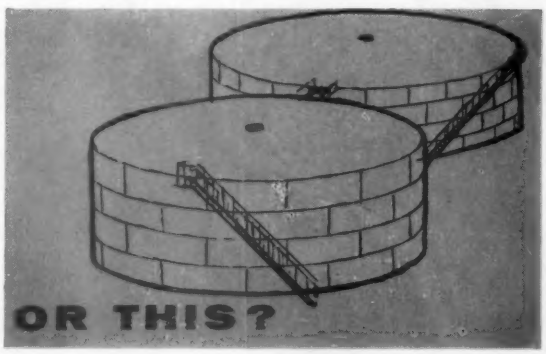

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